JOINT STRIKE FIGHTER
the next generation strike fighter

JOINT STRIKE FIGHTER

Diagnostic, Prognostic and Health Management – a Thirty Year Retrospective

NASA ISHEM Conf. Napa Valley, CA.

7 - 10 Oct 2005

Andrew HESS

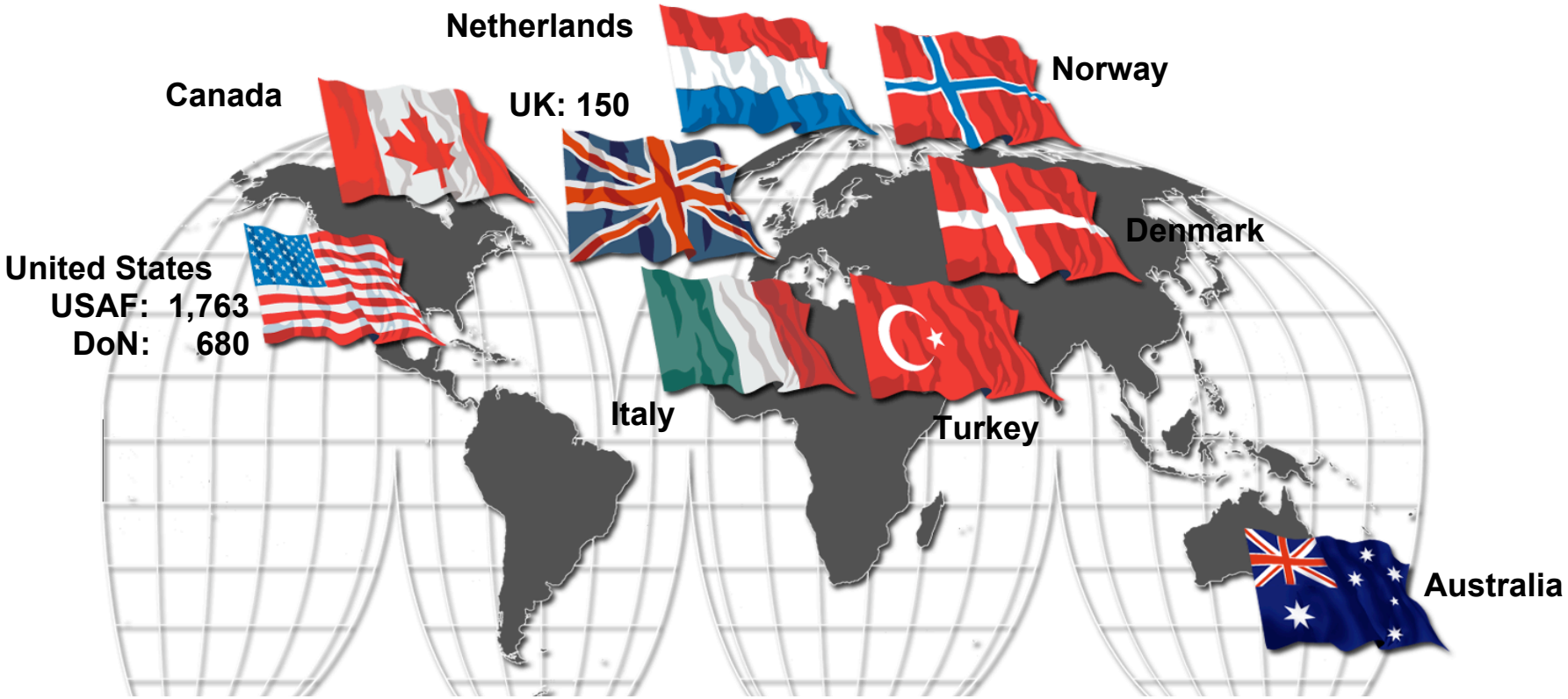
Joint Strike Fighter Program Office

VISION

BE THE MODEL ACQUISITION PROGRAM FOR JOINT SERVICE AND INTERNATIONAL COOPERATION

DEVELOP AND PRODUCE A FAMILY OF AFFORDABLE MULTI-MISSION FIGHTER AIRCRAFT USING MATURED/ DEMONSTRATED 21ST CENTURY TECHNOLOGY AND SUSTAIN IT WORLDWIDE

Service & International Needs



- **USAF:** Multi-role (primary air-to-ground) fighter to replace F-16 & A-10 & to complement F/A-22
- **USMC:** Multi-role, short takeoff, vertical landing strike fighter to replace AV-8B & F/A-18C/D
- **USN:** Multi-role strike fighter to complement the F/A-18E/F
- **UK (RN and RAF):** Supersonic replacement for Sea Harrier and GR-7

2,593 US/UK JSFs ***> 2,000 International JSFs***

What Is JSF?

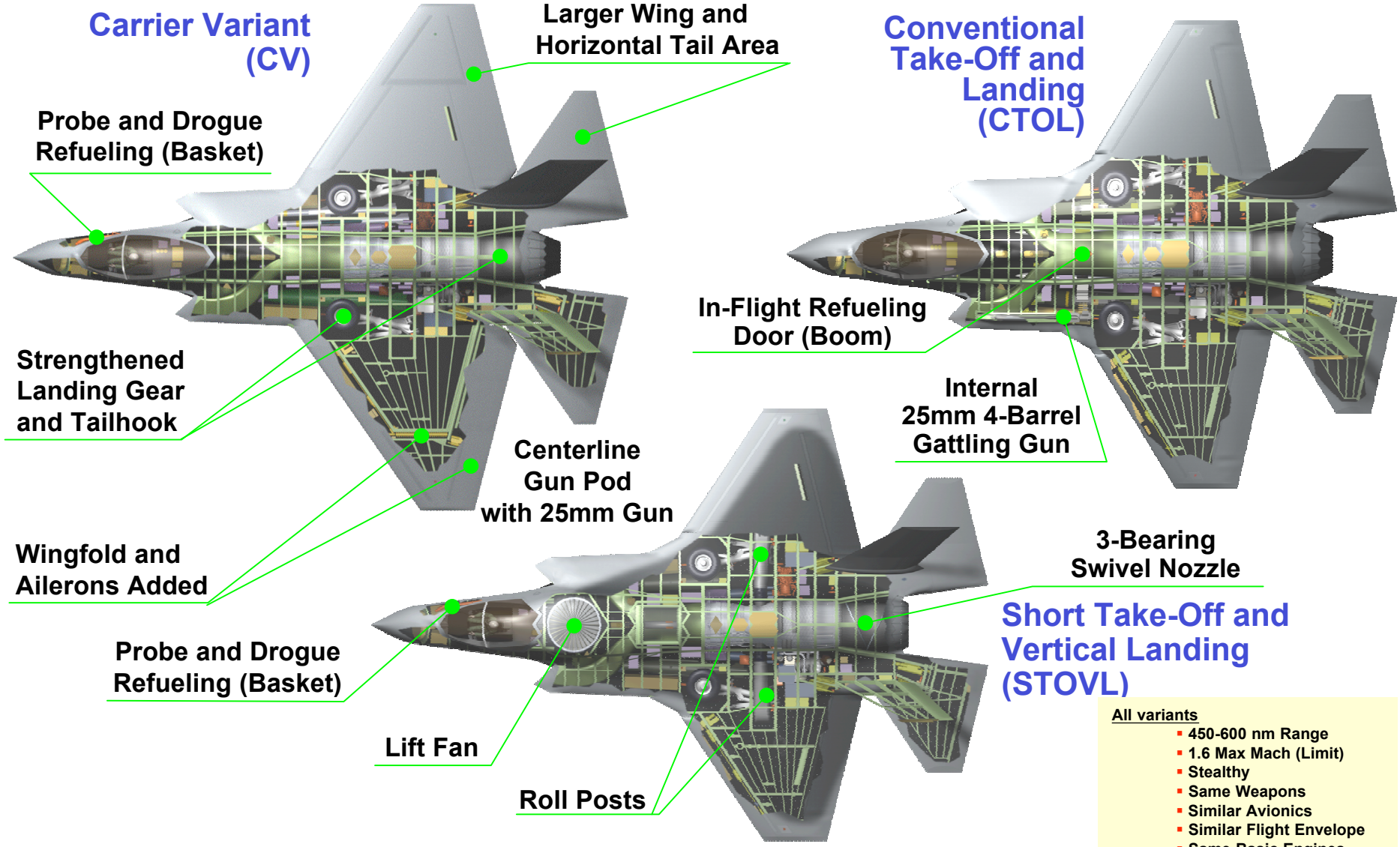
The next generation "family" of strike fighters

- F-16/F/A-18C "like" aero performance
- Stealth signature and countermeasures
- Advanced avionics, data links and adverse weather precision targeting
- Increased range with internal fuel and weapons
- Highly supportable, state of the art prognostics and health management

Lethal Survivable Supportable Affordable

JSF Family Of Aircraft

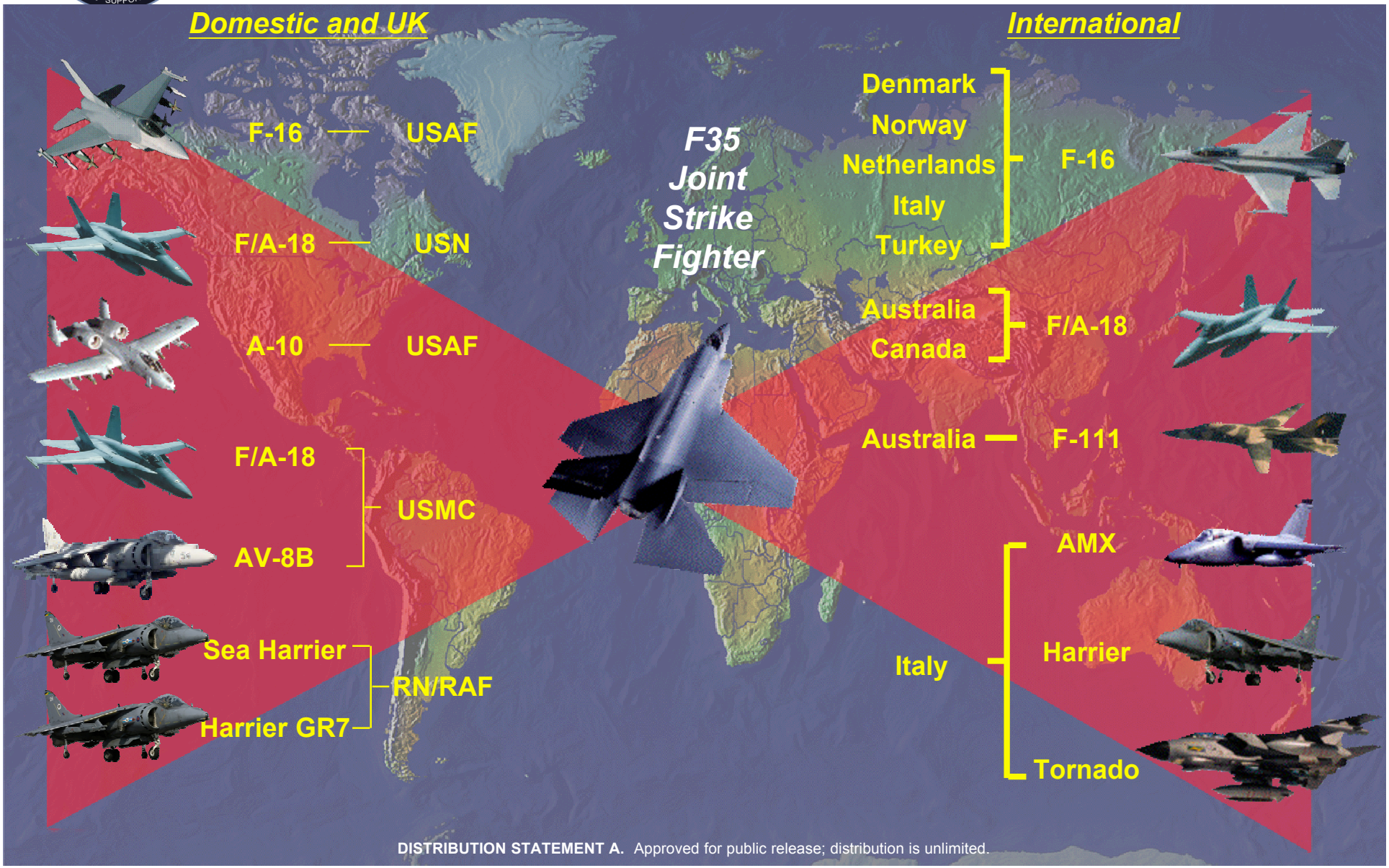
One Program -- Three Variants
Meeting Service and International Needs



All variants

- 450-600 nm Range
- 1.6 Max Mach (Limit)
- Stealthy
- Same Weapons
- Similar Avionics
- Similar Flight Envelope
- Same Basic Engines

JSF Enables True Joint, Coalition Operations



Joint Requirements

BALANCED PERFORMANCE

SURVIVABILITY:

- LO RCS & IR Signature with Combat loads
- Fused Multi-Spectral Situational Awareness
- Real Time Mission Planning to Support Threat Avoidance
- F-16 and F/A-18C "Like" Combat Maneuverability
- Vulnerable Area Reduction

LETHALITY:

- Extended Combat Radius
- Advanced Multi-Spectral Target Detection Capability
- Adverse Weather Capability
- Combat ID at Tactically Significant Ranges
- Suppression of Enemy Air Defenses Capability
- Autonomous Near Precision GPS Targeting Capability
- First-Look - First-Shoot Air-to-Air Capability

SUPPORTABILITY:

- Higher Surge and Sustained Sortie-Generation Rates (SGR)
- Significantly Reduced Logistics Footprint
- Very High Reliability—Reduced Maintenance
- Highly Maintainable

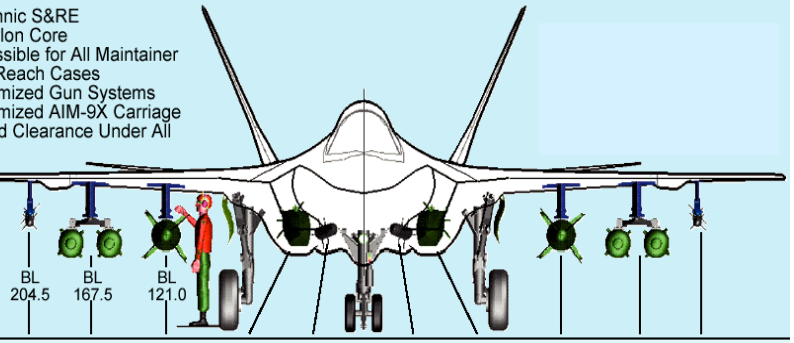
Combat Efficiency and Effectiveness

JSF is a supportable, stealthy strike fighter designed to effectively and affordably counter existing and emerging threats

Joint Requirements

WEAPONS CARRIAGE

- Nonpyrotechnic S&RE
- Common Pylon Core
- Easily Accessible for All Maintainer Height and Reach Cases
- Variant Optimized Gun Systems
- Variant Optimized AIM-9X Carriage
- Deck/Ground Clearance Under All Conditions



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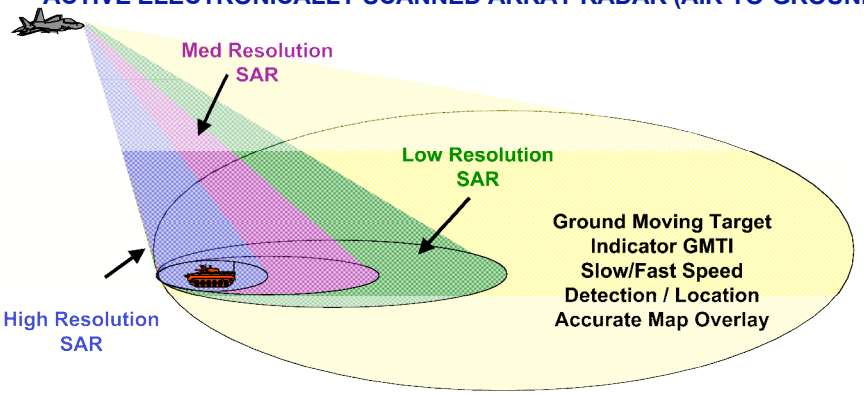
Store Type	A/A	A/A, A/S	A/A, A/S	A/A, A/S	A/A	A/S	A/A	A/A, A/S	A/A, A/S	A/A, A/S	A/A
Weight Capacity	300	2,500 (1,500)	5,000	2,500	350	1,000	350	2,500	5,000	2,500 (1,500)	300

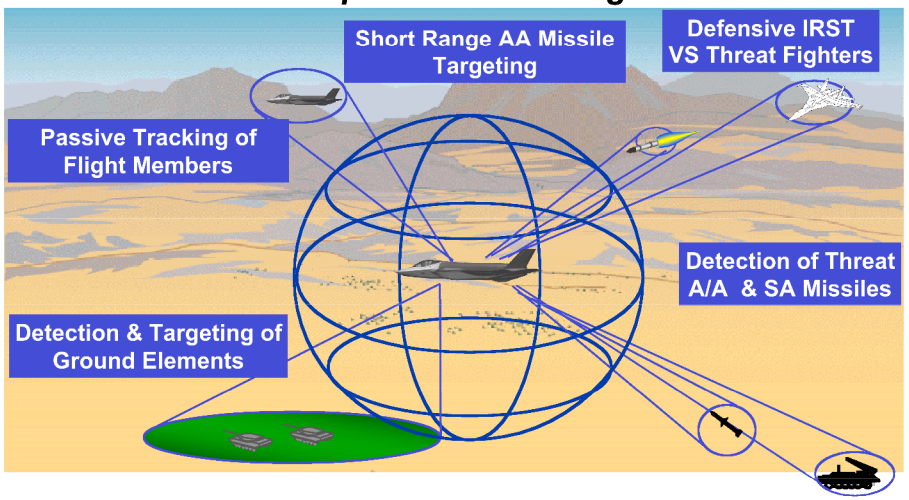
ACTIVE ELECTRONICALLY SCANNED ARRAY RADAR (AIR-TO-GROUND)



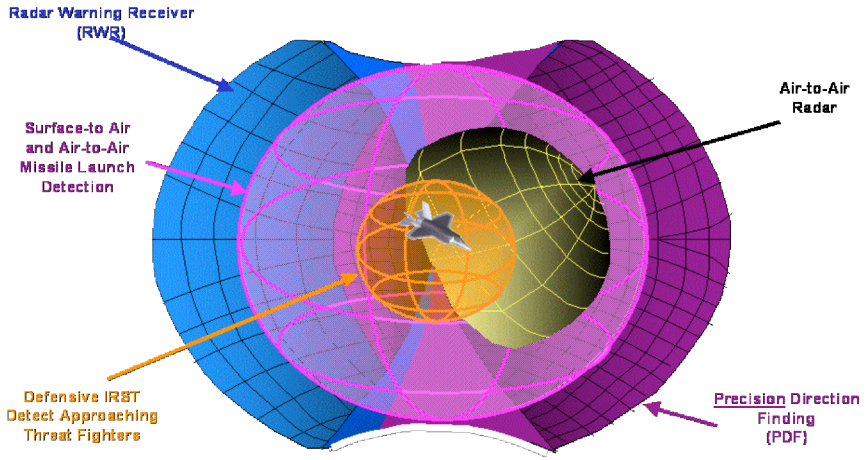
Provides Day & Night Adverse WX, Multi-Mission, Long Range Target Detection and Classification Capability, and Near Precision Self-Targeting Capability With Standard JDAM

DISTRIBUTED APERTURE SYSTEM (DAS)

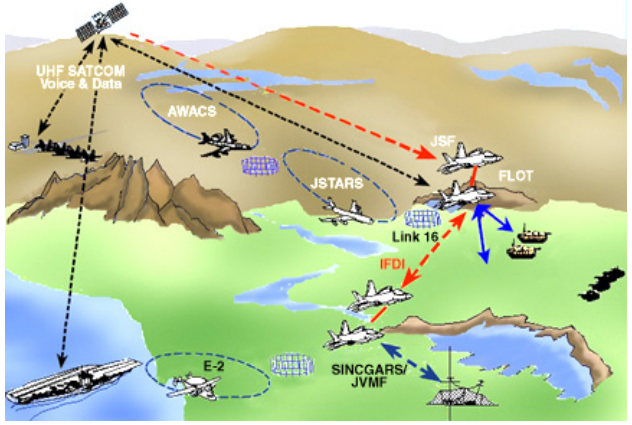
Full Spherical Coverage



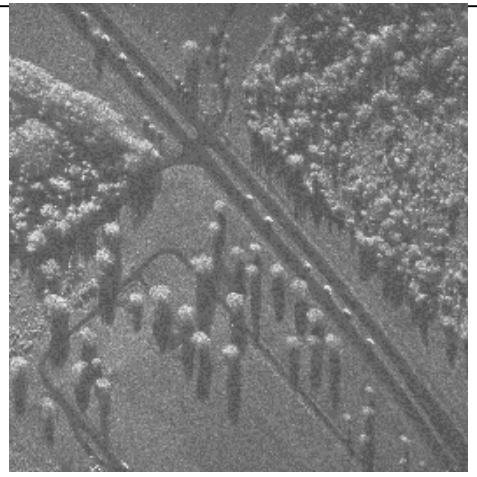
INTEGRATED SENSOR SUITE



JSF Warfighter Capability Highlights



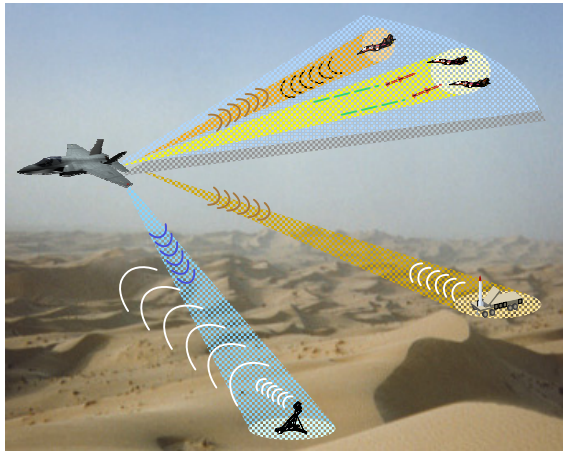
- Cooperative Ops
- Full Off-Board Connectivity



- Multi-Function AESA

- EO Targeting
- Versatile Weapons Capability

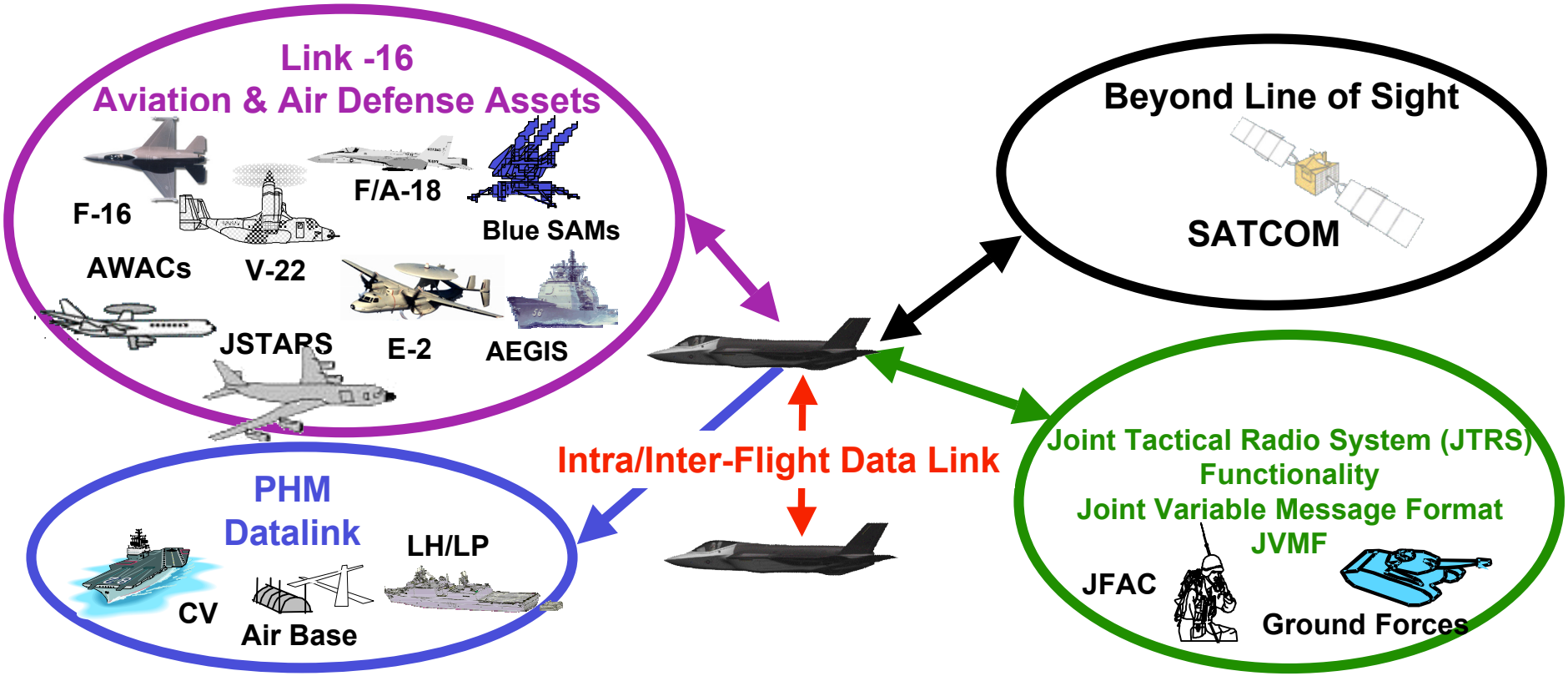
- All Around Situation Awareness



- Passive Precision Emitter Location and Targeting

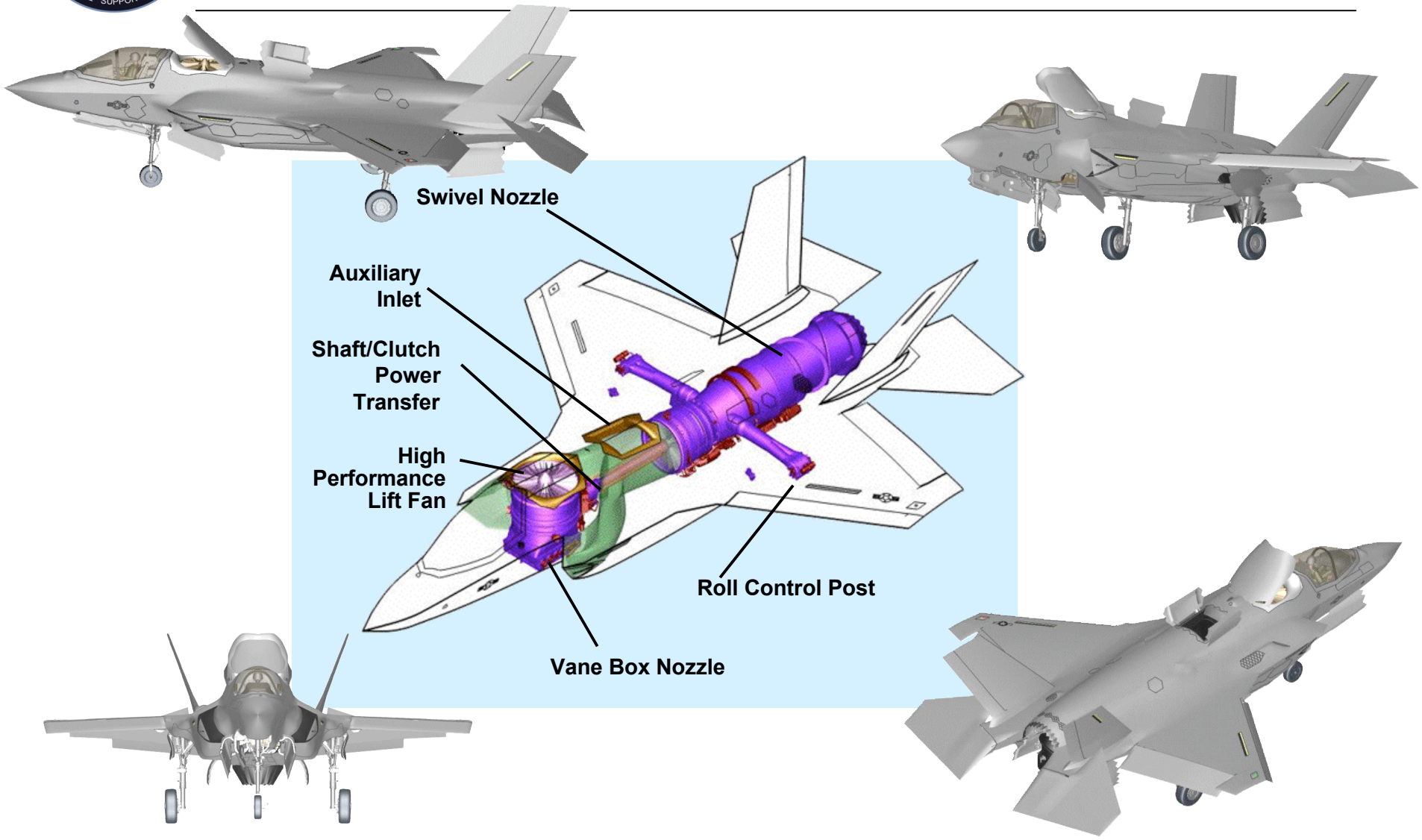
- Fused, Coherent Common Operational Picture

Envisioned Voice and Datalinks Interoperability



Over 120 Information Exchange Requirements to Ensure Interoperability Across US and Coalition Forces

STOVL-Unique Basing Features



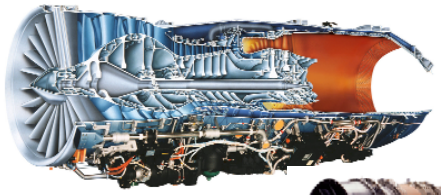
JSF Engine Interchangeability

PRATT & WHITNEY
JSF PROPULSION SYSTEM
F135
ROLLS-ROYCE HAMILTON SUNDSTRAND

F136
A STEP BEYOND

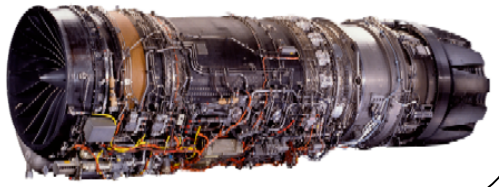
CTOL

- **Physically** and **Functionally** Interchangeable
- Any Aircraft Able to Use Any Engine
- Common JSF Autonomic Logistics System Interfaces



GE AIRCRAFT ENGINES/
ROLLS ROYCE F136

PRATT & WHITNEY F135



CV

STOVL

JSF Engines - - Common Core for Aircraft Variants, Competition in Production

JSF Autonomic Logistics System

Highly Supportable Aircraft

- Smart / Reliable Design
- Prognostics and Health Management
- Remove and Replace (R/R) Maintenance
- On Condition Maintenance

Training System

- Integrated Training
- Embedded Pilot Training
- On Demand Maintenance Training
- Air Vehicle Software Reuse

Support System

- Sustaining Engineering
  - 24/7 Help Desk
- Electronic Joint-Service Tech Data
- Intelligent Maintenance Management
- Global Supply Chain Insight
- Support Equipment Management

Autonomic Logistics Information System

- Distributed Information System
- Enterprise Resource Solution
- Secure
- Scalable
- Deployable

Autonomic Logistics Provides Order Of Magnitude O&S Savings

Autonomic Logistics System Technical Solution

INTEGRATED SUPPORT
- Design Data → Direct to → Support Information
- Failure Prediction → Remove Unit Before Failure

TECHNOLOGICALLY-ENABLED MAINTAINER

FLIGHT OPERATIONS
- Integration for Optimal Mission Performance
- High Sortie Generation Rate
- Low Logistics Footprint

AUTONOMIC LOGISTICS INFORMATION SYSTEM

INTELLIGENT AIR VEHICLE
- Prognostics & Health Management
- Design for Supportability
- High Reliability & Maintainability

Joint Aircrew & Maintainer Training

INTEGRATED TRAINING
- Common, Joint Pilot/Maintainer Training
- Modular, Flexible Training
- Embedded Training

Integrated JSF AL System:
Affordable, Supportable, Survivable, & Lethal

Relative Evolution of Mechanical Diagnostic and PHM Capabilities for Navy Aircraft

Capabilities + Performance

JSF

H-60
H-53
COSSI IMD

V-22

F/A-18E/F

F-14 C/D

E-2C

T-45

F/A-18A/B

AV-8B

F-8

A-7

1970 1980 1990 2000

NAVAL AVIATION SYSTEM TEAM

A-7E Crusader- Engine Monitoring System (EMS)

CAPABILITIES

- Constantly Monitored Parameters
  - Detect all engine anomalies
- Superior Ground Station Software
  - Assisted Maintenance in troubleshooting
- Two Vibration Transducers
  - Fore and aft to cover entire engine
- Developed by Engineers on Carriers
  - More knowledgeable than engineers with no post-flight maintenance experience

ACCOMPLISHMENTS

- Reduced accident rate due to engine failure 90%
- Reduced Maintenance Man-hour/Flight hour rate 66%
- Overall accident rate reduced 66%
- Saved many airplanes just from vibration and VIGV malfunctions alone
- Still the best operational EMS ever produced
- Monitored all aspects of engine - including ignition and generators/starter
- Ground Station had many helpful hints to Assist Maintenance

WEAKNESSES

- Recorded LUI's, but program never put into place to take advantage of them
- Old technology

Relative Evolution of Mechanical Diagnostic and PHM Capabilities for Navy Aircraft

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H-60
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1970 1980 1990 2000

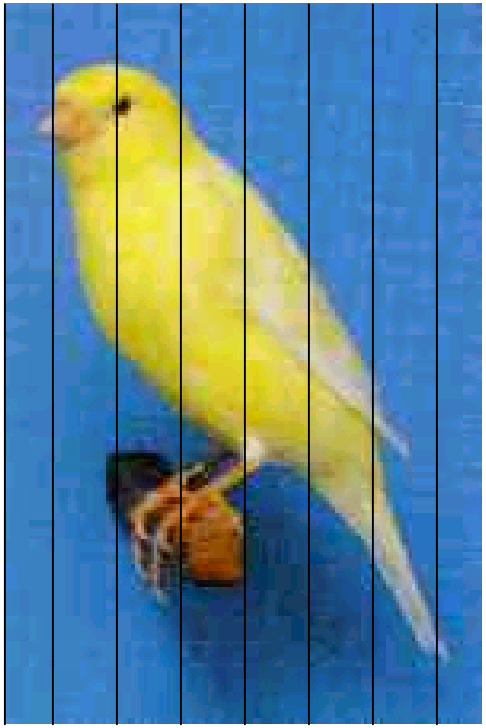
Legacy Health Monitoring

- **Fighters have traditionally stressed diagnostic and usage monitoring with minimal health mangement- some engine health, and BIT on avionics**
- **Structural Usage is often monitored by Strain gauges/ Gmeters - unreliable and incomplete picture**
- **BIT is inaccurate and has very high false alarm rates**
- **Operational Exceedance monitoring is rudimentary without maximizing the benefits**

Legacy Systems Will Not Get Us Where We Need To Be

Shift in Condition Monitoring Paradigm

Old Way



New Way

The ability to monitor has been around for a long time, but now we have the technology to really do something with it.

Current Logistics Structure

Ability to Predict Future Health Status

Max Life Usage

MAX SGR

Ability to Anticipate Problems and Req'd Maint Actions

High Availability

Better FD/FI Efficiency

Quick Turn Around Time

Small Logistics Footprint

No RTOK

Performance Based Maint

Accurate Parts and Life Usage Tracking

Low # of Spares

No False Alarms

Maintenance Mgt

Configuration Tracking

No Surprises

Opportunistic Maintenance

Mission Planning

Short and Responsive Supply Pipeline

No/Limited Secondary Damage

No/Min Inspections

Limit Impact of Quality Control Problems

Too Large & Costly

System Performance Feedback

Immediate Access to all Available Information

Manned Space Application Logistics Structure from a Needs Perspective

Ability to Predict Future Health Status

MAX SGR

Max Life Usage

Ability to Anticipate Problems & Req'd Maint Actions

High Availability

Small Logistics Footprint

No CND

Min Inspections

Better FD/FI Efficiency

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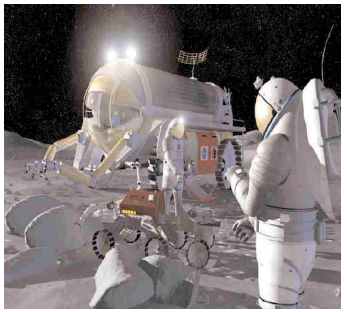


Maintenance Mgt

Configuration Tracking

Opportunistic Maintenance

Mission Planning

Fault Accommodation and System Reconfiguration

No/Limited Secondary Damage

Enhanced Safety of Flight

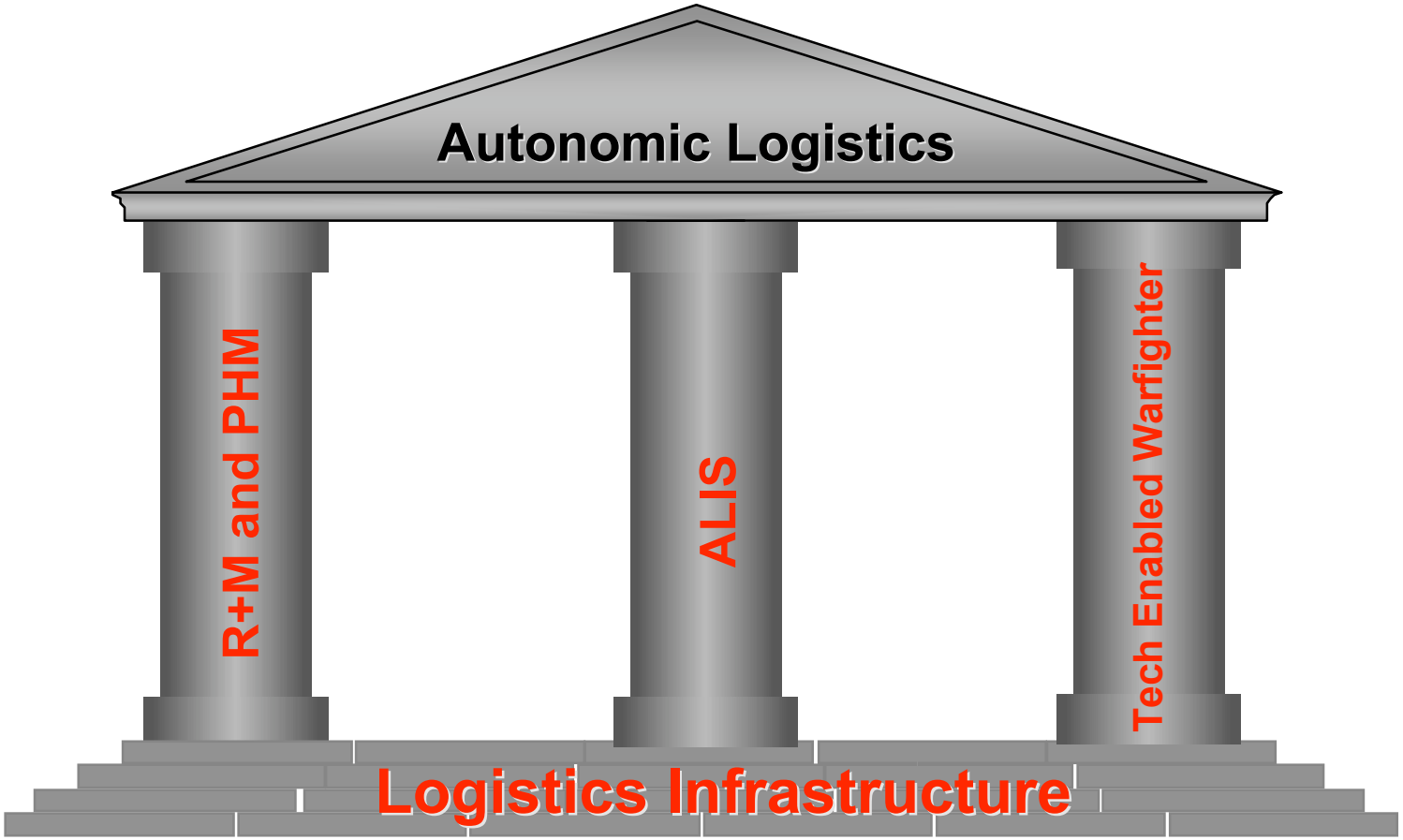
Too Costly & Too Risky

Limit Impact of Quality Control Problems

System Performance Feedback

Immediate Access to all Available Information

Key Elements of JSF Autonomic Logistics



Affordable, Survivable, Maintainable, Supportable

Operationally Available and Lethal

Prognostics and Health Management

- **Why Did We Choose This Technology?**
  - **Enable Autonomic Logistics**
  - **Enhance Flight Safety**
    - **Single Engine Aircraft, Must Have Dual Engine Reliability**
  - **Increase Sortie Generation Rate**
  - **Eliminate False Alarms**
  - **Eliminate CND's and RTOK's**
  - **Reduce Life Cycle Costs**
  - **Maximize PHM Benefit from Limited Specialized Sensors**
  - **Take Max Advantage of the "Smart" Digital Aircraft**

Natural Evolution of Legacy Diagnostic Capabilities Coupled with the Added Functions, Capabilities, and Benefits offered by New Technologies

Prognostics and Health Management

What is it?

- **Enhanced Diagnostics –the process of determining the state of a component to perform its function(s), high degree of fault detection and fault isolation capability with very low false alarm rate**

- **Prognostics – actual material condition assessment which includes predicting and determining the useful life and performance life remaining of components by modeling fault progression**

- **Health Management – is the capability to make intelligent, informed, appropriate decisions about maintenance and logistics actions based on diagnostics/prognostics information, available resources and operational demand.**

GOALS OF PHM

- Enhance Mission Reliability & Aircraft Safety
  - Single engine aircraft must have dual engine reliability
- Reduce Maintenance Manpower, Spares, & Repair Costs
- Maximize Lead Time For Maintenance & Parts Procurement
- Eliminate Scheduled Inspections and Enable CBM:
  - Opportunistic maintenance reduces A/C down time
- Provide Real Time Notification & Health Reporting
  - Only tells pilot what NEEDS to be known immediately
  - Downlink info & "answers" inflight
  - Informs maintenance & autolog of the rest
- Aids in Decision Making & Resource Management
- Reduce Life Cycle Costs
- Eliminate CNDs & RTOKs
- Detect Incipient Faults & Monitor Until Just Prior to Failure
- Catch Potentially Catastrophic Failures Before They Occur
- Maximize PHM Benefit from Limited Specialized Sensors
- Take Max Advantage of the "Smart" Digital Aircraft

PHM Constituent Functions and Processes

- Fault Detection
- Fault Isolation
- Advanced Diagnostics
- **Predictive Prognostics**
- Useful Life Remaining Predictions
- Component Life Tracking
- Performance Degradation Trending
- **False Alarm Mitigation**
- Warranty Guarantee Tracking – Data Enabling New Business Practices
- Selective Fault Reporting
  - **Only tells pilot what NEEDS to be known immediately**
  - **Informs Maintenance of the rest**
- Aids in Decision Making & Resource Management
- Fault Accommodation and Possible Reconfiguration
- Information Fusion and Reasoners
- Information Management
  - **Right info to right people at right time**

System Overview

- **JSF Prognostics and Health Management (PHM) Includes:**
  - ***Built in Test (BIT)***
    - Power-On Self-test (POST)
    - Continuous Self Test (CST)
    - Initiated BIT (IBIT)
  - ***Prognostics***
    - Application of Technologies That Permit the Advance Notification of Impending Failure and Condition Based Maintenance
  - ***Enhanced Diagnostics (beyond legacy FD/FI)***
  - ***Life Usage Tracking***
  - ***False Alarm Mitigation***
  - ***Health Assessment & Management***
- **PHM Is Divided into:**
  - ***Subsystem PHM (Supplier)***
  - ***Subsystem Applications / Integrity Managers (Product Teams)***
  - ***System Level PHM (PHM Team)***

DETECTION, ISOLATION & PROGNOSIS

Detection

Through sensors, Models etc

Isolation

Information fusion from sensors, Models etc.

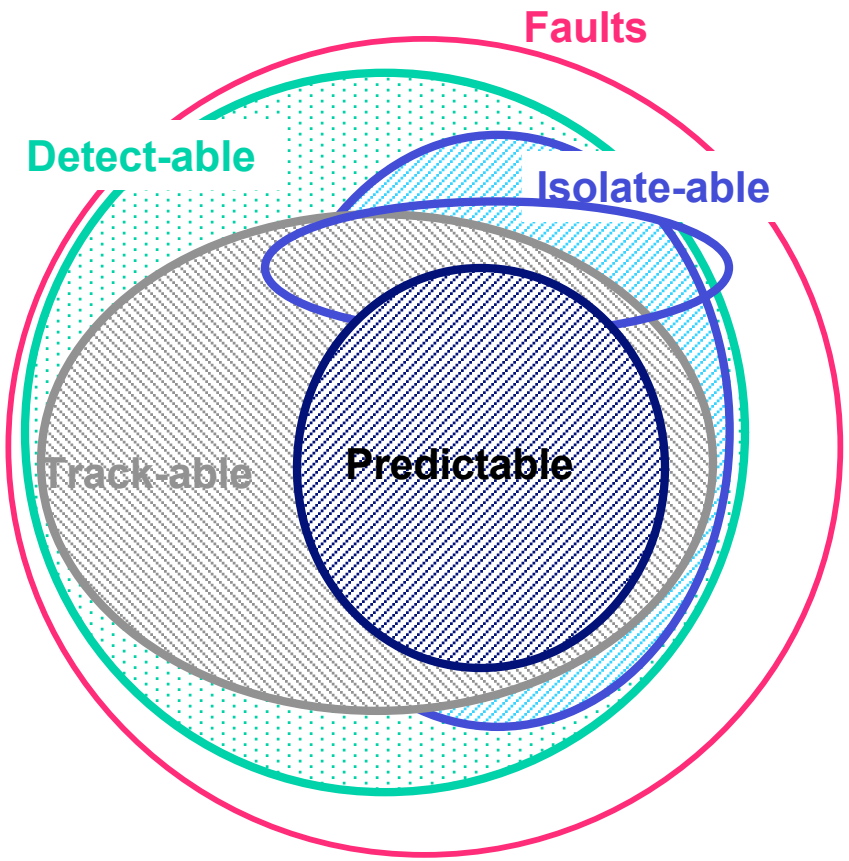
Tracking/Trending

Processed PHM data

(Off board PHM)

Prediction/Prognosis

Based on tracking/trending, & lifing models



JSF CDP AVPHM/ALIS Demos Provided Substantiation of Weapon System PHM

5
- Operational Loads Monitoring
- Overload Analysis
- Force Management
- Elimination of Unnecessary Inspections
- Usage Tracking / Life Projection

2
- FOD Detection/Classification
- System Correlation/Confirmation
- Shaft Misalignment Detection
- Lift Fan Safe Operation
- Condition Based Maint.
- Elimination of Unnecessary Inspections

4
- Improved FD/FI
- FD/FI w/o Add'l Sensors
- Failure Impact Assessment
- Optimization of Supply Chain Management

Structures

Utilities & Subsystems

Propulsion

Mission Systems

3
- Improved FD/FI
- Fault Confirmation
- Post-Flight Data Analysis
- Manufacturer Feedback
- Reduction of OEM Trouble-Shooting Time
- CND/RTOK Elimination

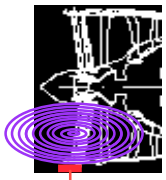
Mission Sys/ Utilities & Subsystems

ALIS Off-Board PHM

1
- FD/FI and Confirmation
- Failure Impact Assessment
- In-flight Mission Replanning
- Autonomic Triggering of AL
- Prognostics
- Cooperative Operations

6
- Assist Maintainer in Difficult Failure Analysis
- Resolution Sharing for Fleet
- Rapid/Effective Interface to Engineering
- Knowledge Discovery

Examples of Some Advanced Sensors and Non-Traditional Detection Techniques



Acoustic FOD Detector (AFD)

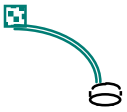
Eddy Current Blade Sensor (ECS)
GDATS

Ingested Debris Monitoring System (IDMS)

Engine Distress Monitoring System (EDMS)
Smith

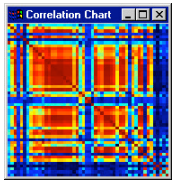
Chip Detector

Advanced Vibration

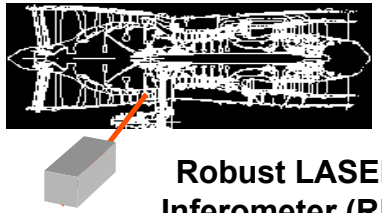


Piezoceramic Patch Crack Detection (PZT)
UTRC

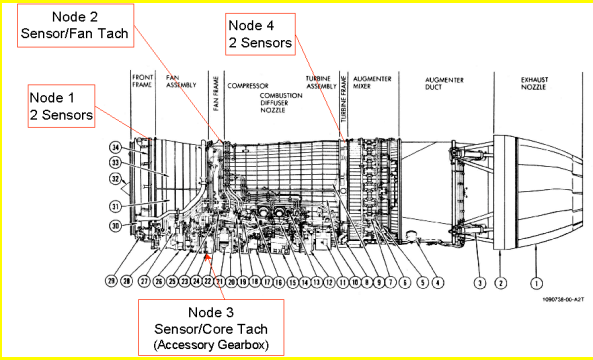
Blade Vibration Meter (BVM8X)
Hood Technology



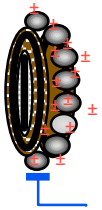
Beacon-Based Exception Analysis for Maintenance (BEAM) JPL



Robust LASER Inferometer (RLI)
Epoch Engineering

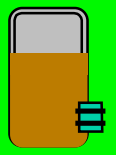


MEMS Sensors



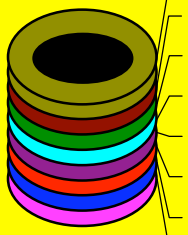
Electrostatic Bearing Monitor (EBM)
Smith

Electrostatic Oil Debris Monitor (EODM)
ExperTech/SHL

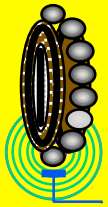


Oil Condition Monitor (OCM)
UDRI

F119 Oil Debris Monitor (ODM)
GasTOPS

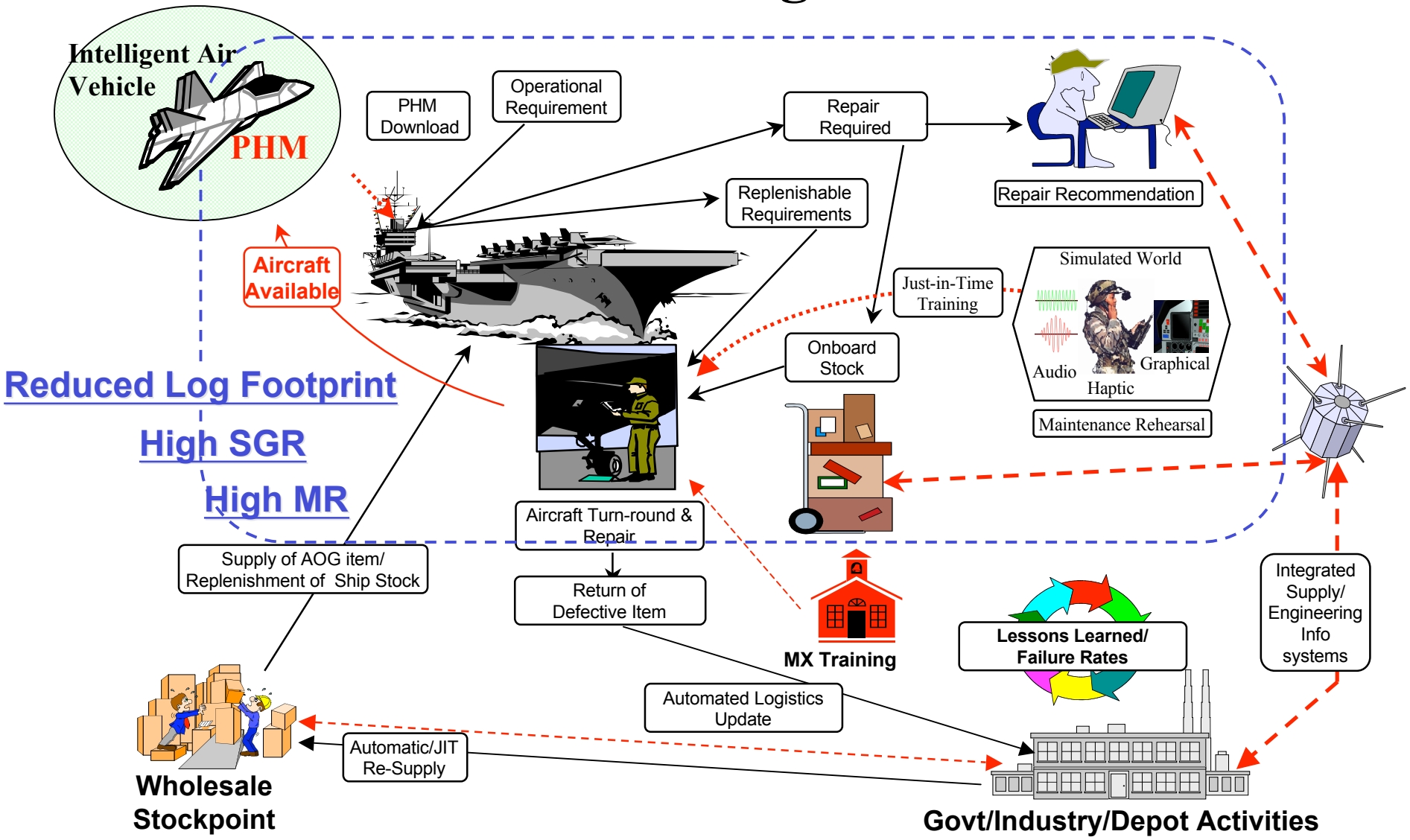


ICHM



Stress Wave Analysis (SWAN)
DME

PHM Is the Air Vehicle Enabler of the Autonomic Logistics Structure



PHM Architecture

Reasoner Approach Benefits:

- Enables Use of Few Specialized Sensors
- Enhance Capability to Use Existing Data & Parameters
- Greatly Reduces False Alarm Rate
- Enables Detection and Fault Interaction Across Sub-systems

M - Parameters

Minimum Number of Specialized Sensors

Existing Aircraft Parameters

Advanced Algorithms

Integrate Into

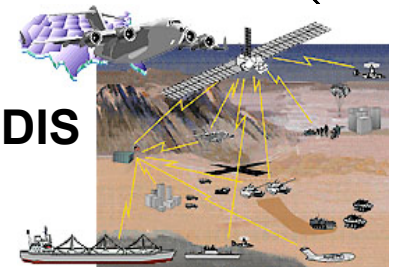
N-Area Reasoners

- PROPULSION
- STRUCTURES
- Vehicle Systems
- MISSION SYSTEMS
- SUBSYSTEMS
- VMS

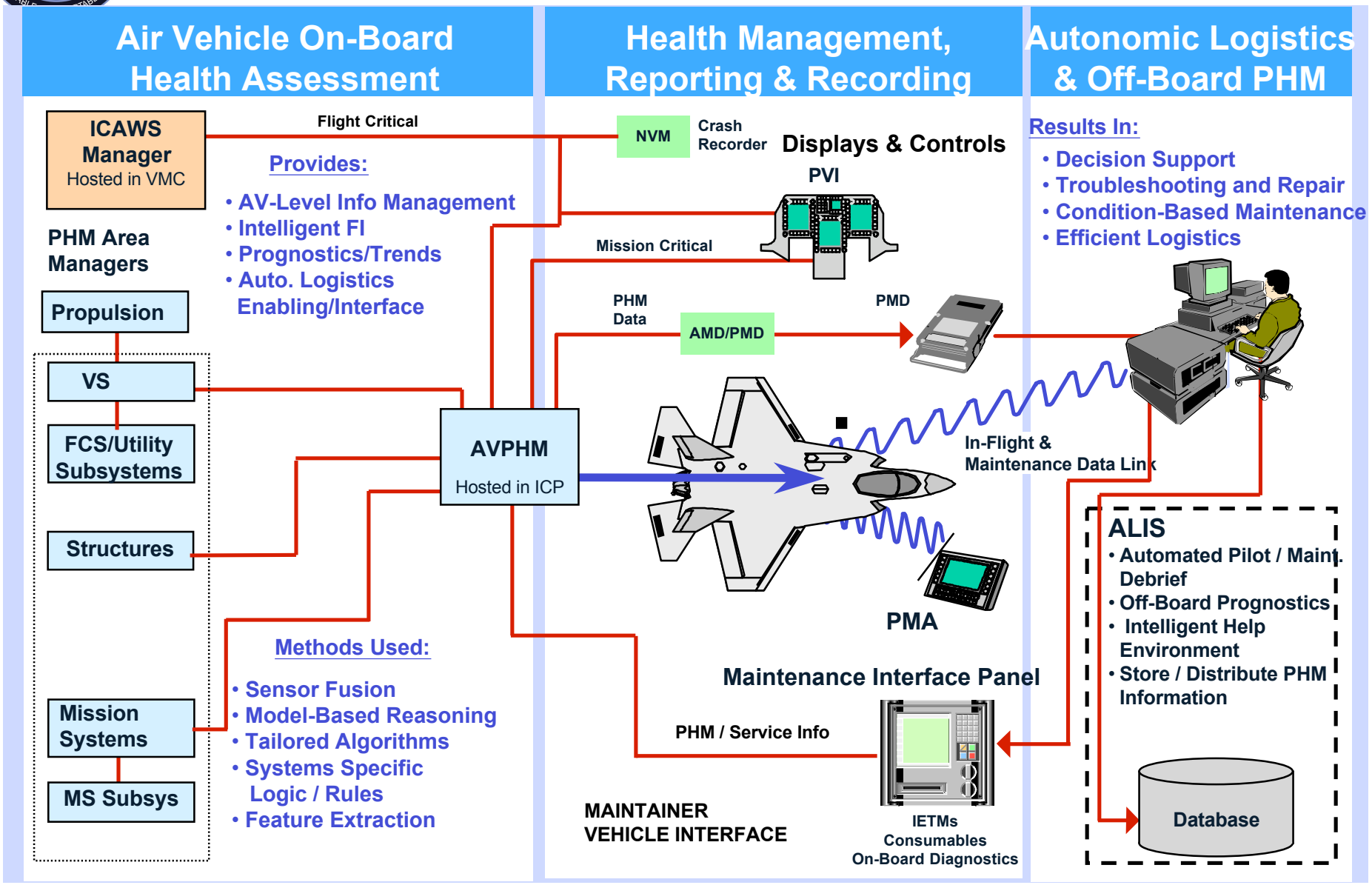
Feed Data for Correlation and Reporting

AIR VEHICLE REASONER

JDIS

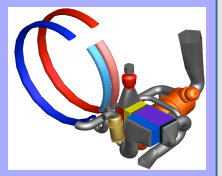
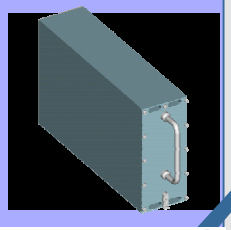


PHM Architecture and Enabling Technologies

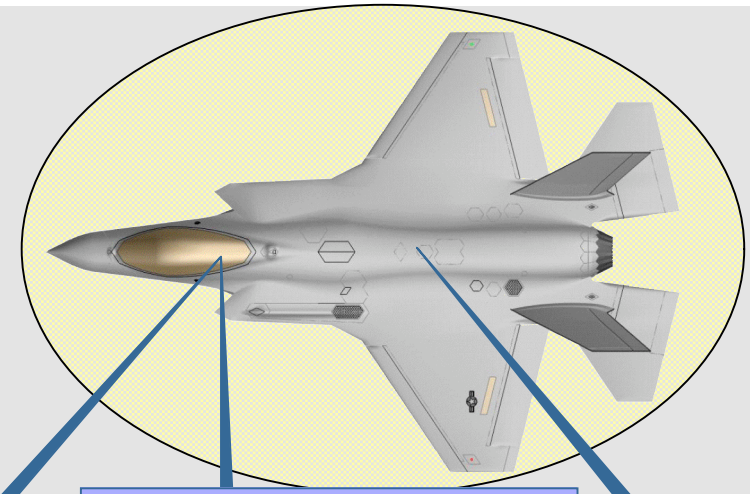


Air System PHM IPT Products

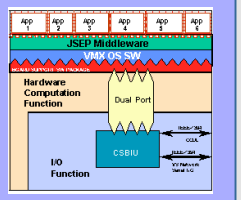
VS/MS PHM SEIT - Optimal Diagnostic / BIT Capabilities for Subsystem IPT's


- Diagnostics / BIT
- IPT's / supplier teams achieve the best and most cost effective coverage
- Pertinent data acquisition at sensor, component and sub-system levels.
- Requirements, top level design, use cases, verification.



VS/MS/AF PHM Area Managers (products)

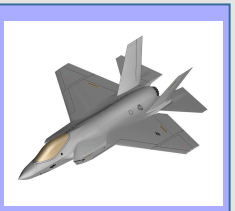


- Enhanced diagnostics, System models, Corroboration, Correlation, and Information fusion
- Prognosis Collect data, Compute life usage Predict time to failure

Off-board PHM (product)

- Prognosis models,
- Failure resolution algorithms
- Diagnostic Tools

Air Vehicle PHM (product)



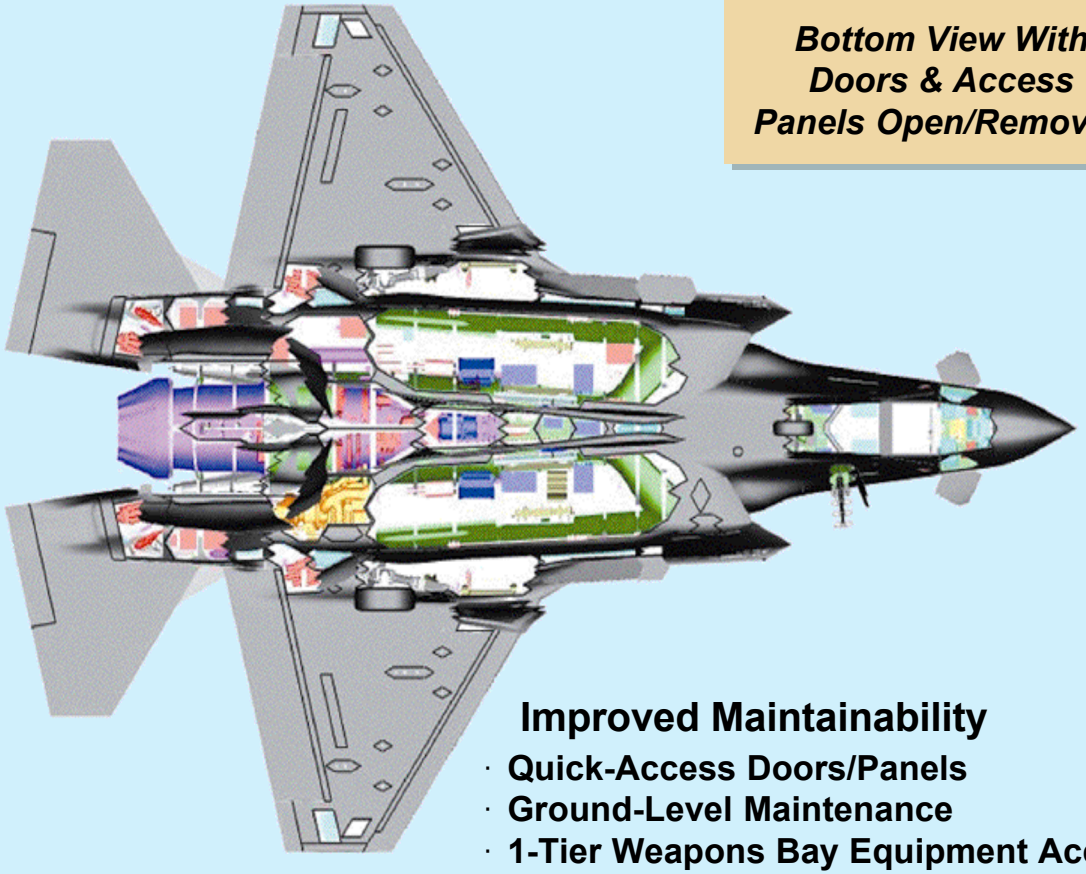
- Health management Report Remaining Functionality
- Information broker for on- and off-board users
- High-level service requirements for data reduction, file management

SUPPORTABILITY FEATURES & PHM

Improved Reliability
- Liquid-Cooled Avionics Backplanes/Convection Cooled Components
- More-Electric Secondary Power
- Durable Seals & Coatings
- Requirements Allocated to Suppliers

Self-Sufficiency
- Non-Pyro Weapons Release
- On-Board Ground Power/Cooling
- On-Board Maintenance Panel
- Integrated Combat Turnaround Without Aircraft Support Equipment

Integrated PHM
- Architecture Demonstrated
- Equipment Functionality Defined – Requirements Allocated to Suppliers
- Reliance on Symptom Correlation vice sensors



Bottom View With Doors & Access Panels Open/Removed

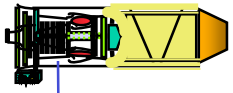
Improved Maintainability
- Quick-Access Doors/Panels
- Ground-Level Maintenance
- 1-Tier Weapons Bay Equipment Access
- Conduction-Cooled Modules (Liquid in Rack Only)
- Tail-Over-Water Servicing/Wpns Loading

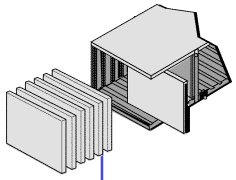
PHM APPROACH INCLUDES ELEMENTS OF ENTIRE SYSTEM

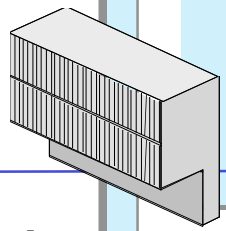
Subsystem Level Prognostics & Health Management

Propulsion

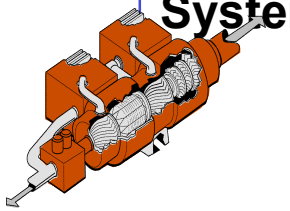
Mission Systems



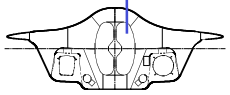




Vehicle Systems

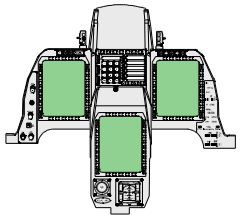


Subsystems

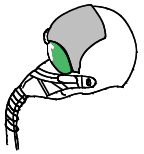


Structures

System Level Failure Management, Reporting & Recording



- Cautions, Advisories, Warnings
- Mission Critical Systems Status



Pilot Vehicle Interfaces

Air Vehicle Manager

Maintainer Vehicle Interfaces

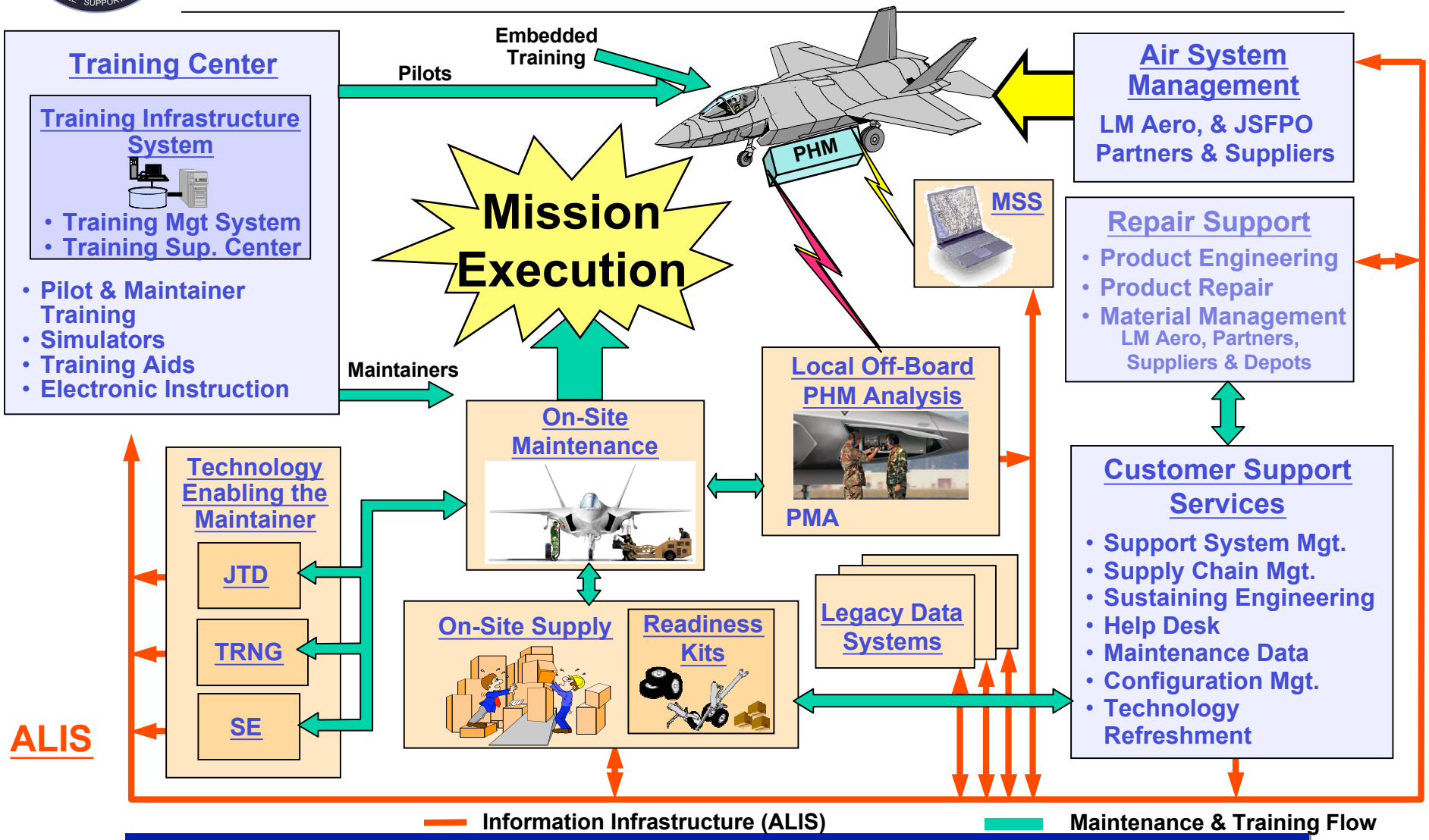
Portable Maintenance Device

- Single-Point Up/Download
- Tech Information

Distributed Information System (DIS)

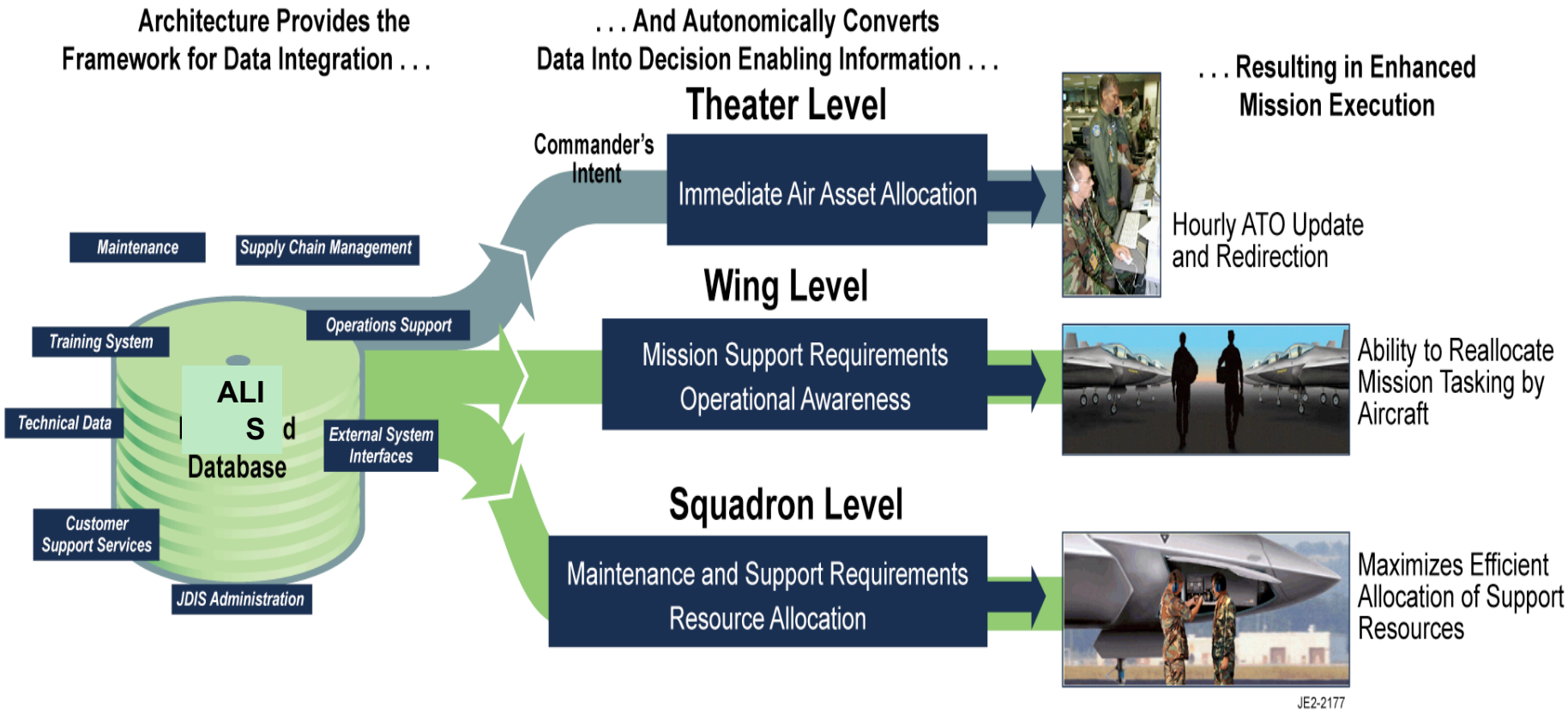
- Sortie Generation
- Operations & Maintenance
- Design Feedback

AUTONOMIC LOGISTICS SYSTEM



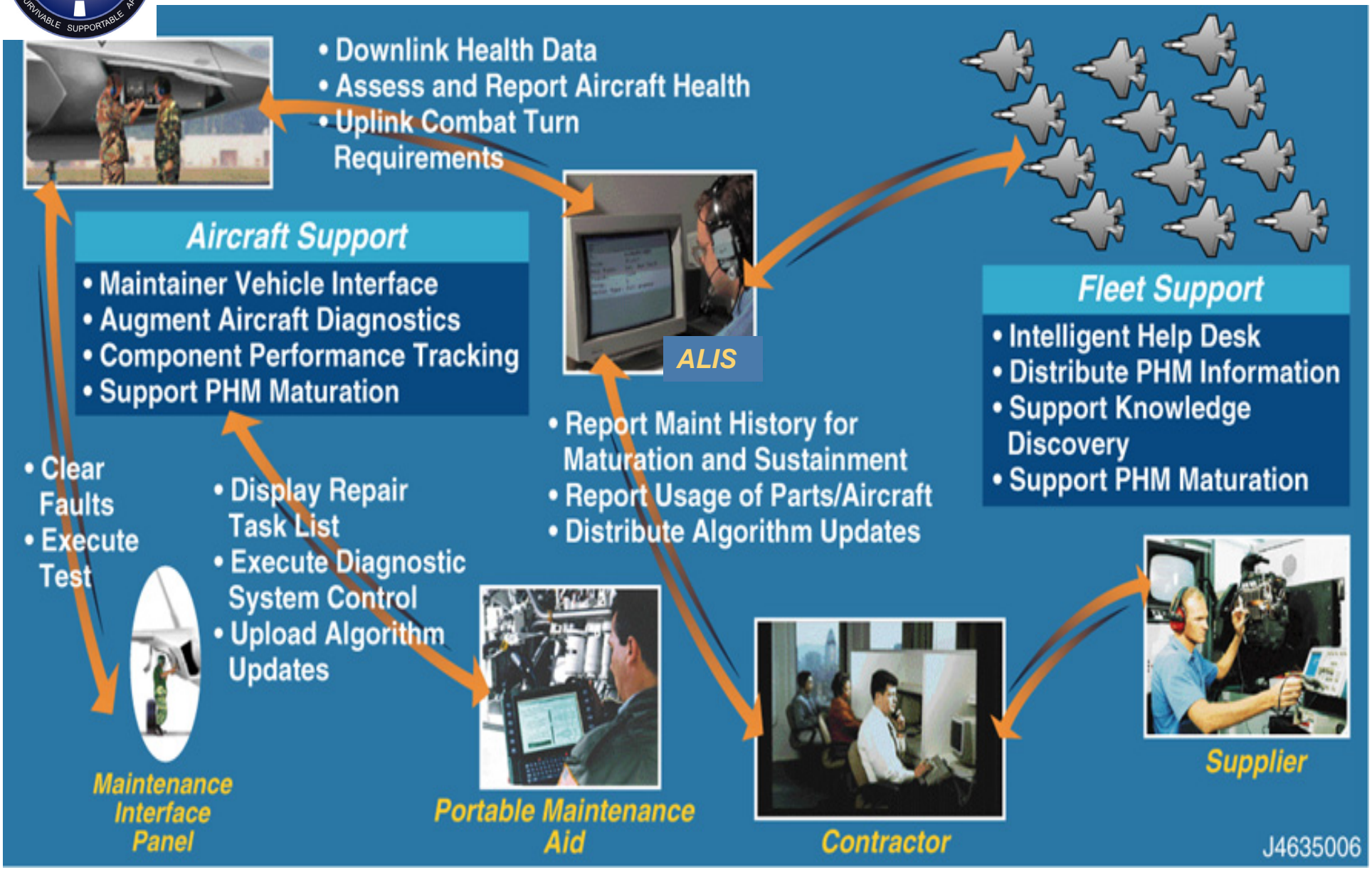
Autonomic Logistics Provides Faster Repair with Fewer People Resulting in Increased Air Vehicle Availability at a Lower Cost

AUTONOMIC LOGISTICS INFORMATION SYSTEM (ALIS)



Provides Timely, Total Logistics Support

Off-Board PHM Overview



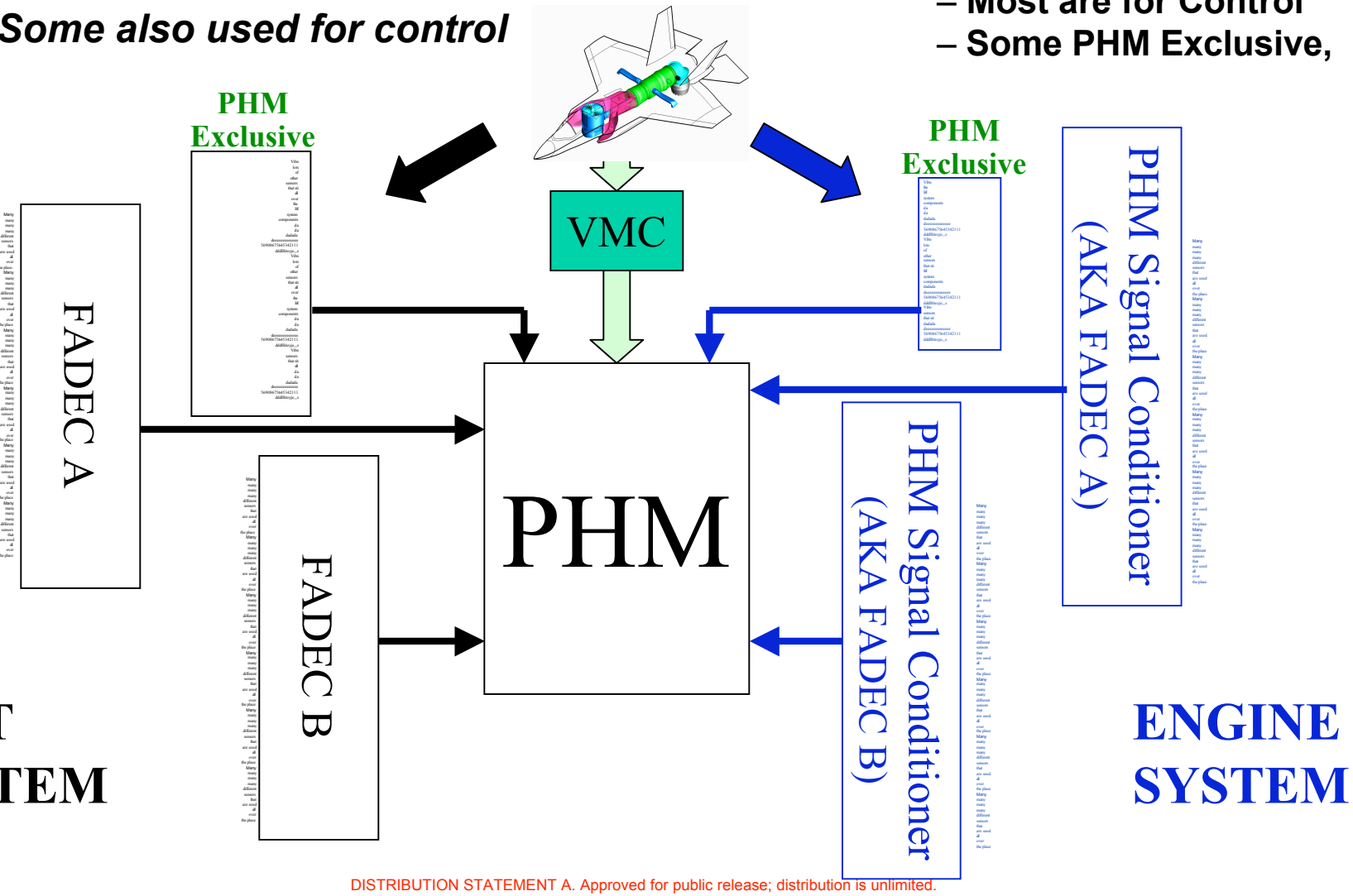
Example Propulsion PHM Elements….Sensors

Sensors are part of the solution

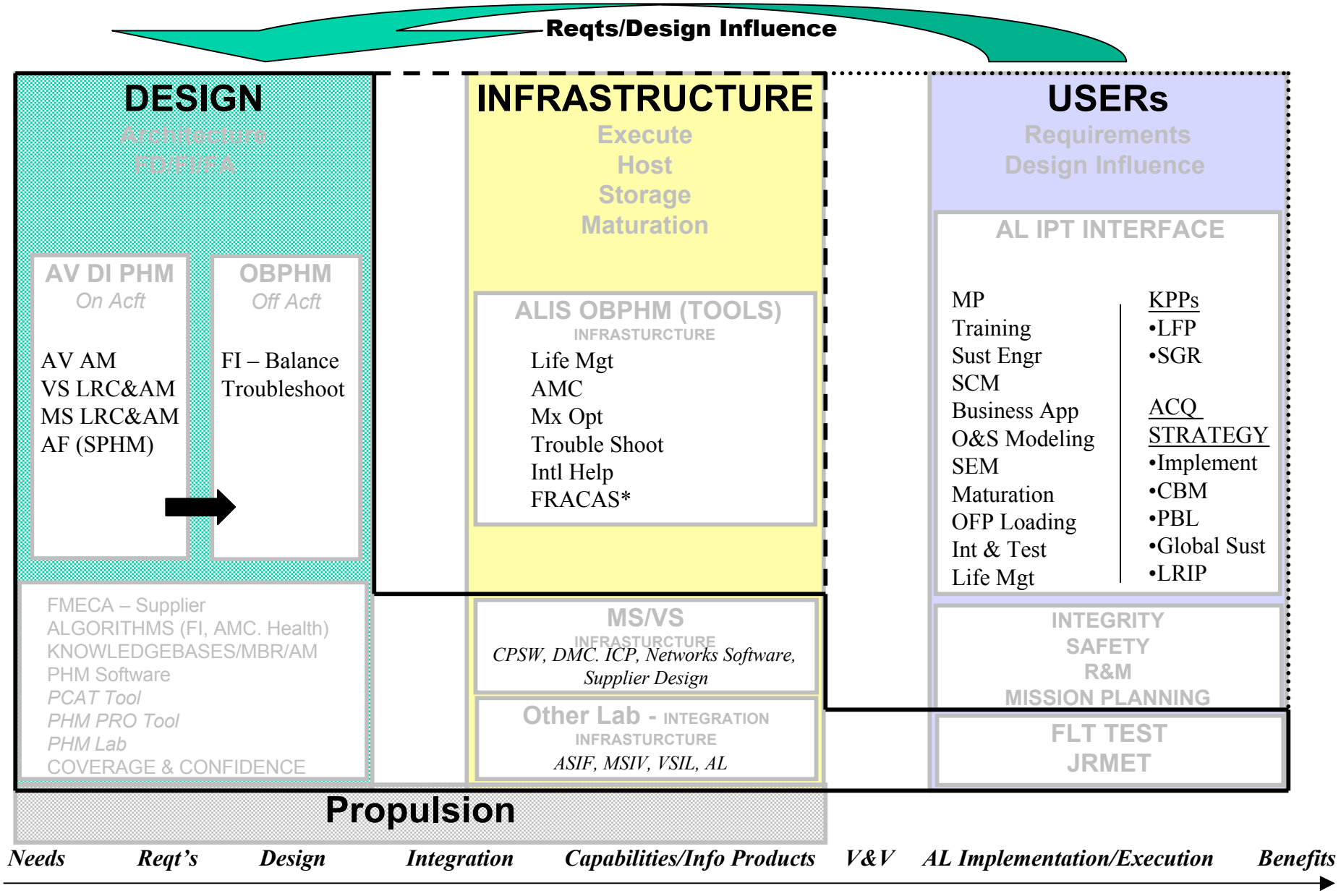
All Sensors are PHM Sensors

...Some also used for control

- **Many Signals**
  - **Most are for Control**
  - **Some PHM Exclusive,**



PHM BIRDS EYE VIEW



PHM Redefines Design Criteria

- **Old**
  - **Safety and Supportability are a Function of Reliability, Redundancy, and the Support Concept ~ *Ensures***
- **New**
  - **Safety and Supportability are a Function of Reliability, Redundancy, PHM Capabilities, and the New Support Concept ~ *Drives***
- **PHM Capabilities can be used as Design Attributes to Support Trade Studies**

PHM and Autonomic Logistics Allow Paradigm Shifts in the System Design Process

Ever Increasing Computer Power

Accurate Time to Failure Predictions

Autonomic Logistics

Model Based Techniques

CBM

Information Fusion

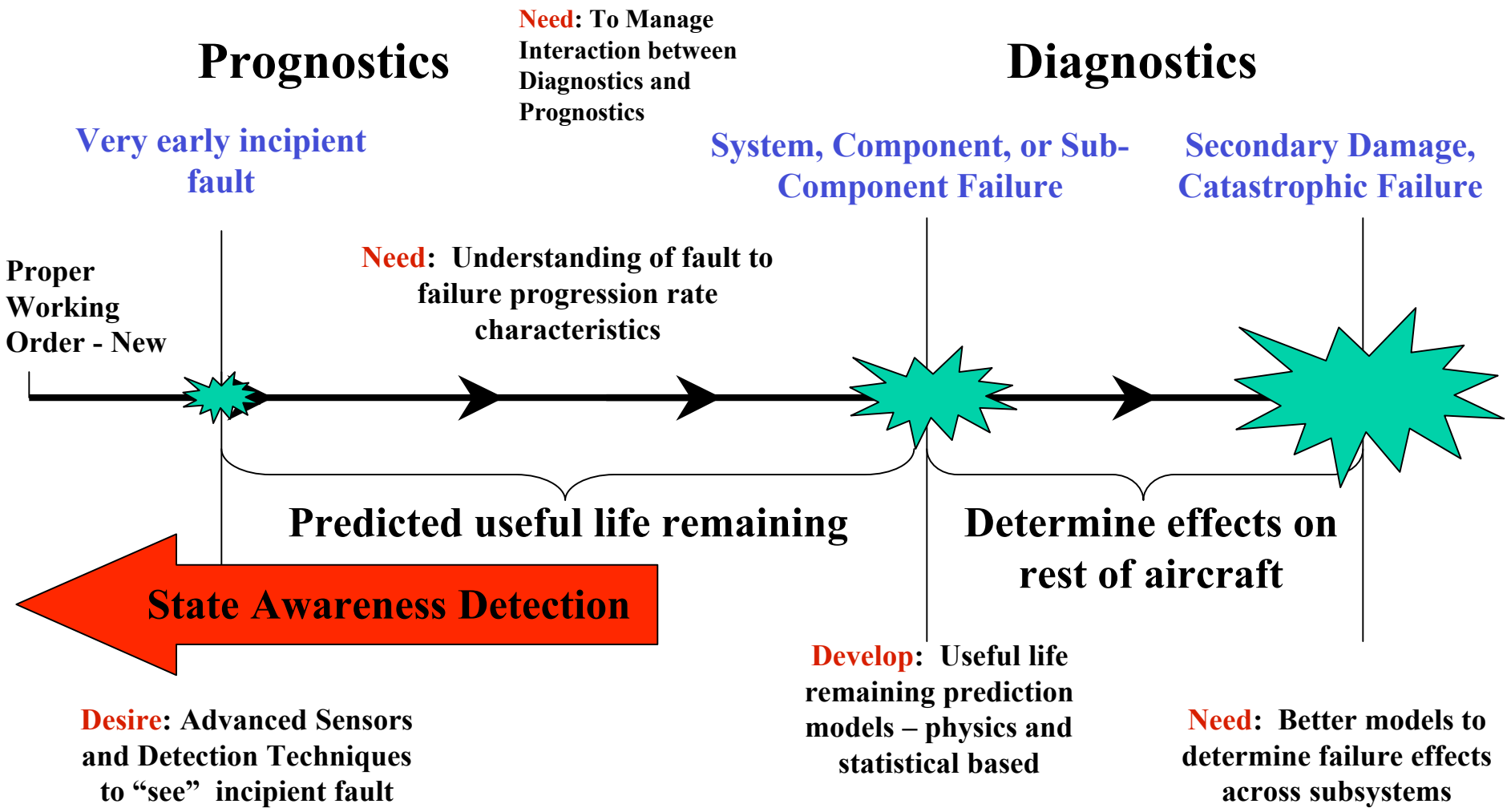
Useful Life Remaining

No False Alarms

Advanced Sensors

Prognostics - Dream or Reality?

Failure Progression Timeline



The Goal is To Detect "State Changes" as Far to the Left As Possible

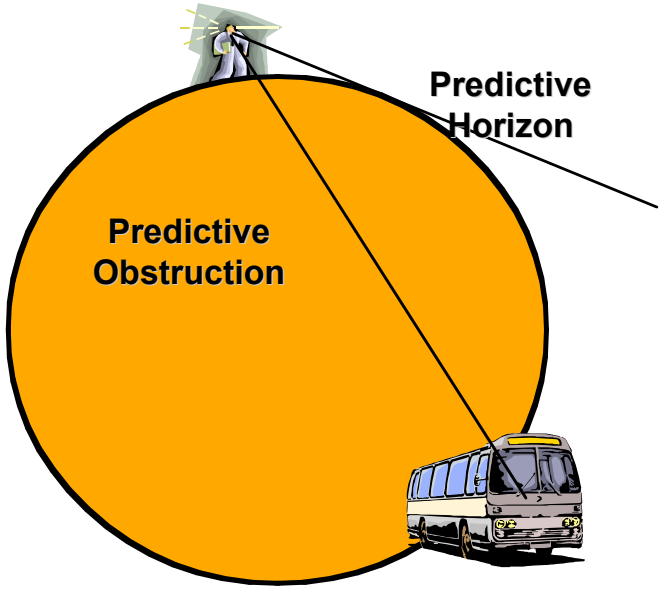
Prognostic Perspectives & Questions

Prognostic Horizon Level Targets

How Far Do You Want to See Into the Future?

Prognostics: What's Your Perspective?

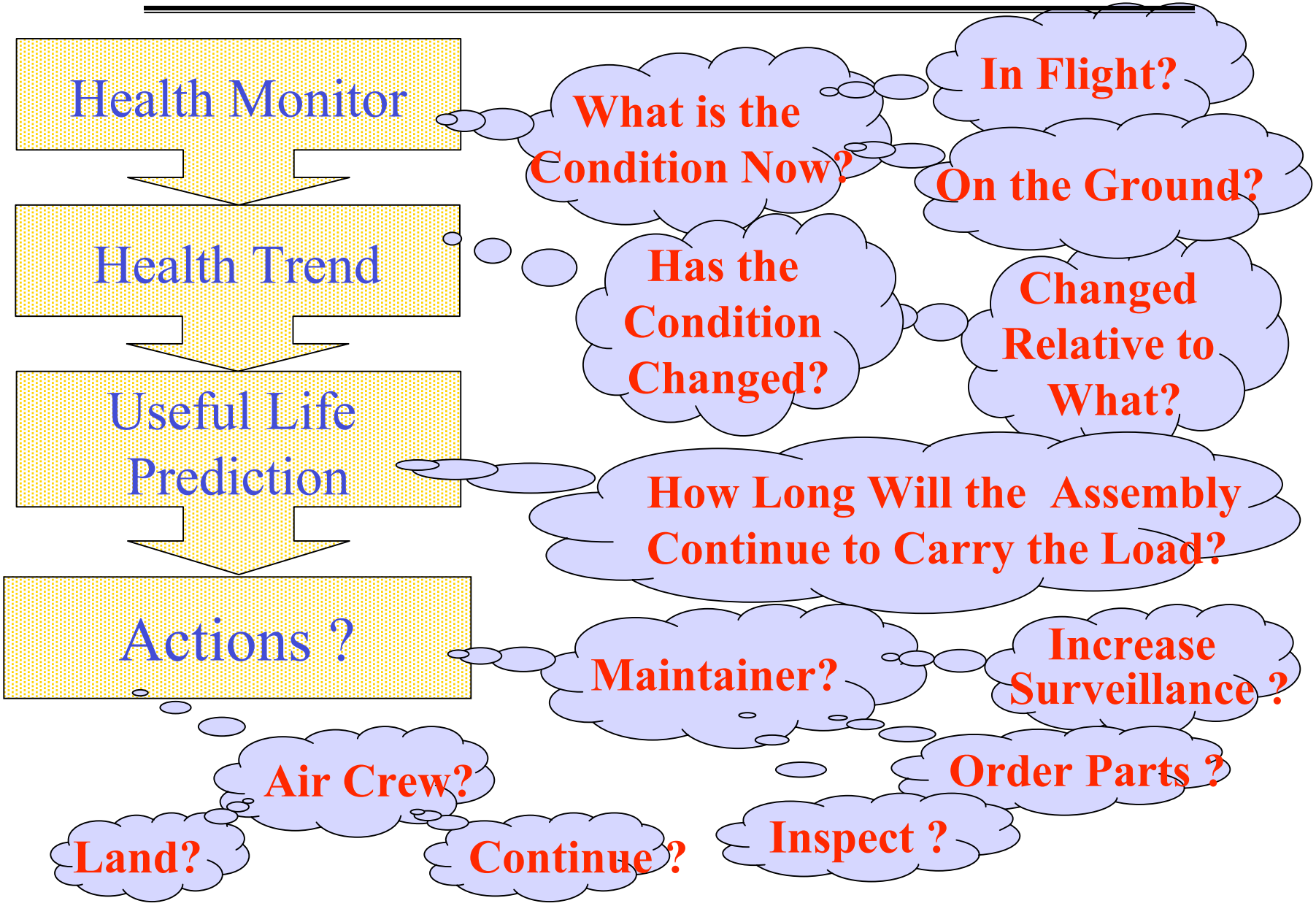
- Needs and Benefits
- Capabilities: Available and Desired
- Technology "Holes" to be Filled
- Philosophy and Strategy
- Integration and Implementation
- Questions:
  - Is It Possible?
  - How are you going to use It?
  - What's Good Enough?



Choose One

- Detect Bus Just Before it Hits You, or
- Detect Bus Far Enough in Advance to Take The "Right" Evasive Action

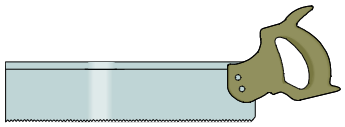
Predicting Health (Prognostics)



Diagnostic & Prognostic Toolkit

Knowledge of Failures

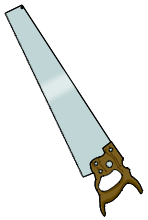
Impact of Secondary Damage

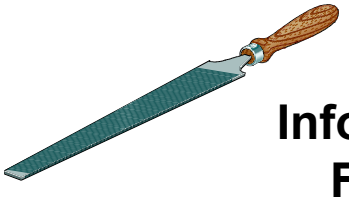


rule-based systems

Multiple Indicators and Analysis

Accurate Sensors





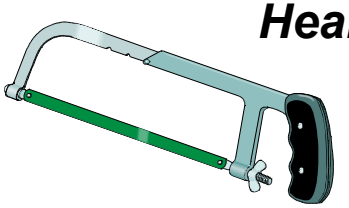
Information Fusion

MEMS

Model Based Techniques

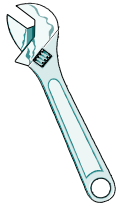
Performance Data

Determination of LRU Health At Any Point in Time



Neural Networks

fuzzy logic



Accurate Algorithms

Understanding Physics of Failures

Techniques for Data Scatter and False Alarms

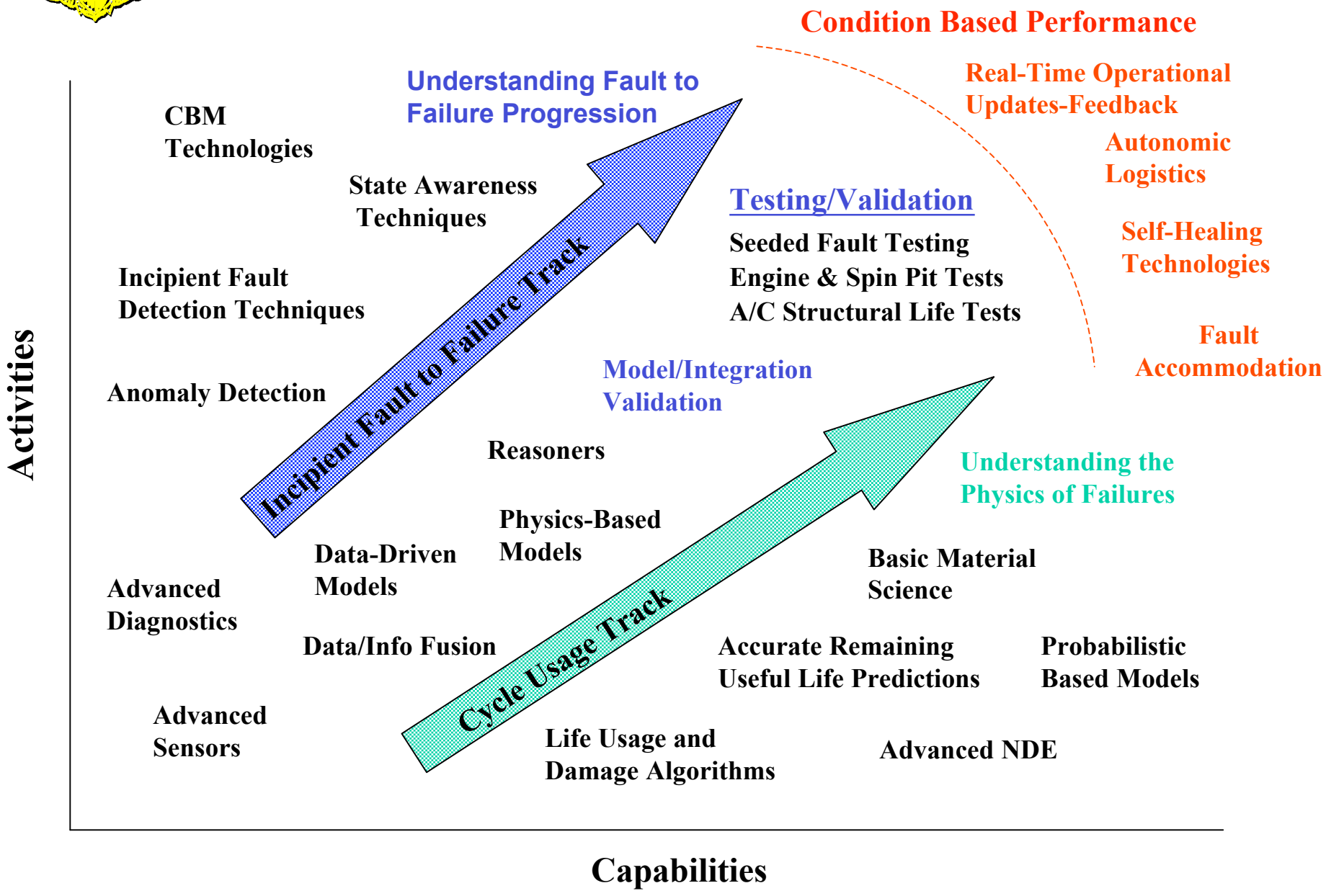
casual networks

Reasoners

NAVAL AVIATION SYSTEM TEAM

Notional

Roadmap to Predictive Prognostics



Category Definitions

Category 1 – Defined physics of failure with historical basis
- ***Algorithm will be mature at implementation***
- ***Maintenance threshold will be set and require only verification***

Category 2 – Defined physics of failure without historical basis
- ***Algorithm will be mature at implementation***
- ***Maintenance threshold will require maturation through analysis or field failures***

Category 3 – Suspected relationship without historical basis or technology
- ***Data will be gathered with the purpose of establishing an algorithm***
- ***Maintenance threshold will require maturation***

Category 4 - Perceived value without known technology
- ***General aircraft data will be gathered and applied to algorithm as need is determined***

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Prognostics Maturation Strategy

Use E&MD Data to V&V Models

Use Condition Based Performance Predictions

ID Components and Sub Elements Suitable for Prog.

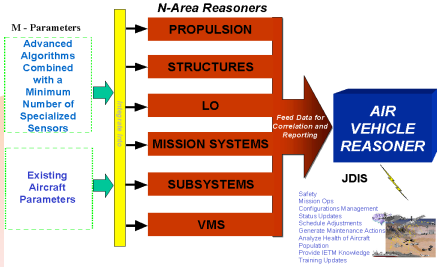
ID Technologies to Use

Eliminate Those that Are not Technically or Economically Feasible

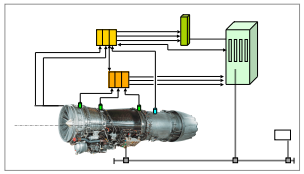
Modify Algorithms to Account for Real World Considerations

Intelligent Air Vehicle

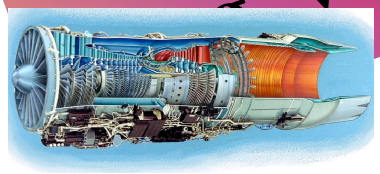
PHM



Tech Integration



Tech Maturation



System Investigation

Develop State Awareness Techniques

Perform Seeded Fault Tests

Understand "Physics of Failure"

Combine All Aspects into Air Vehicle

NAVAL AVIATION SYSTEM TEAM

Notional strategy to demo predictive prognostics on helo drivetrain

- **Identify and Target Components and Sub-elements suitable for Prognostics**
  - **Those with understandable fault to failure progression characteristics**
  - **Eliminate those impossible or too hard to consider**
- **Develop and/or Obtain advanced models**
  - **Fault to failure progression characteristics**
  - **Useful life remaining**
- **Perform experimental seeded fault tests**
  - **As many as affordable**
  - **Try to understand the physics of the failure**
- **Verify and validate models**
  - **Using seeded fault and blind test data**
- **Modify useful life remaining prediction model to account for real world considerations**
  - **Mission Profiles**

PHM Diagnostic Needs

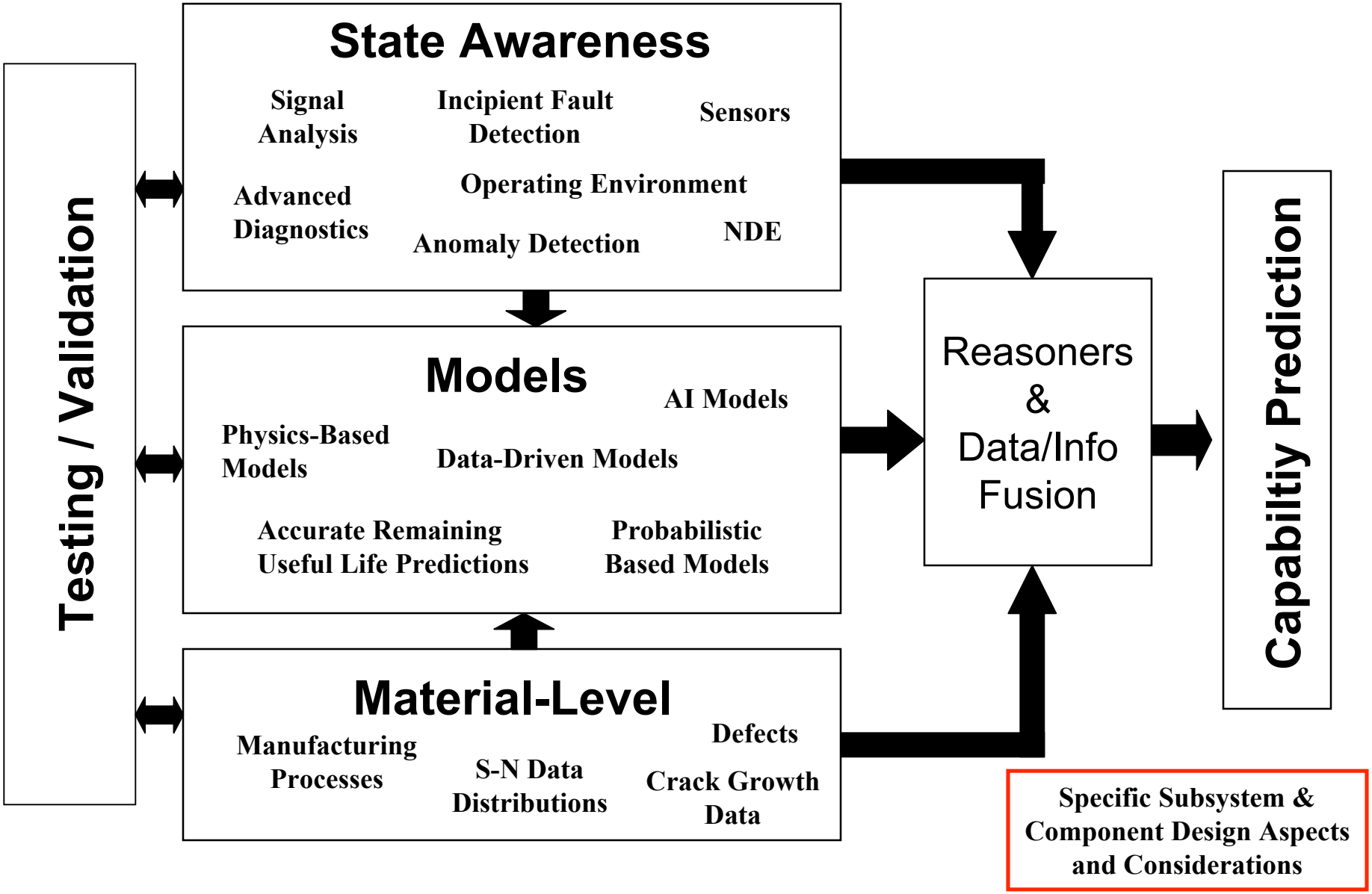
- **More "Two-for" and "Three-for" Sensors**
- **Methods for Leak Detection**
- **Better Corrosion Detection**
- **More Data Fusion Methods**
- **More Analysis of Failure Effects on Other Sub-systems and Components**
- **Better Understanding of Maintainer Time Breakdown**
  - **Gives Better Estimates of LCC Models**

Prognostics: What We Are Missing

- **Better Understanding of Physics of Failure**
- **Condition Based Performance Predictions**
- **Better State Awareness Techniques**
- **Better Understanding of Incipient Crack Growth**
- **Better Understanding of Fault/Failure Progression Rates**
- **Better Understanding of Material Properties Under Different Loading Conditions**
- **Better Data Fusion Methods**
- **Cost Benefit Models to Determine Practicality of Prognostics**
  - **Risk vs. Reward**
- **Better Knowledge of Effects of Failures Across the Air Vehicle**
- **Study to Determine What Components to Perform Prognostics On**

Notional

Predictive Prognostics - Integration Tasks



Lessons Learned

- **Performance Based Specs "are Not Ideal" for PHM**
  - **If you Know What you Works and you want, Specify it**
  - **If you Know What doesn't Work, write a Spec Req't so you don't get it**

- **The big Prime Contractors want to be System Integrators but don't Necessarily have the "niche" Technologies and Expertise to Provide Fully Capable, State-of-the-Art PHM Capabilities**
  - **If a technology or capability isn't Mature and COTS, they don't want it**
  - **Keeping Management Commitment among Design/Cost Pressures through the course of the Development Program is very Challenging**

- **Much of the New and Innovative PHM Technologies and Capabilities are Reside in the Small Business arena**

- **Look for Feeder Technologies for New PHM Capabilities in other Related and Non-Related Disciplines and Industries**
  - **e.g., much of the Advanced Vibration Diagnostics used in Gearbox Monitoring came out of the signal processing and data analysis techniques found in ASW**

Lessons Learned

- **PHM is a Multi-Disciplined, Multi-Functional, Multi-Technology, Multi-Faceted Endeavor**
  - **Understand this and Plan to Deal with it**
- **On-Board and Off-Board PHM Capabilities Need to be Designed and Developed at the Same Time, Together, and Integrated by the Same Prime Contractor**
- **On-Board and Off-Board PHM Algorithms Need to be the Responsibility of the On-Board, Air Vehicle, Subsystem Specific Engineering Design Teams**
  - **This includes Development, Validation, and Verification**
- **Mission System and Avionics Infrastructure Issues can Significantly Limit PHM System Development and Maturation**
  - **Dependence on their Hardware, Through put, Processing, Storage, Software, etc. to Implement our Capabilities**
  - **They are always a Problem and always let you down**

Lessons Learned

- **PHM as a Robust Data Acquisition System will Surprise you as it aids in Addressing TBD Problems that it wasn't Designed to Address**
- **More Data is Better. Learn to Handle it and Manage it.**
  - **Even with a Fully Automatic PHM, Pilot Recording is Useful**
- **PHM, R+M, System Integrity, and Safety Disciplines are Married at the Hip**
- **Autonomic Logistics or its equivalent is PHM's main Customer, but they Easily Fall Back on Legacy Supportability Approaches. Their Effectuation is Extremely Important but Difficult**
- **PHM Must be Part of the Overall System Design Process and its many Trade Studies**

Lessons Learned

- Prognostics Capabilities are mostly Hard to Develop, take Time to Mature, but are Doable in Many but Not all Cases
  - Identify Cases that are Not Doable and don't Worry about them
  - Focus limited Resources on Doable and High Value Components

- Need Good Diagnostics before Doing Prognostics
  - Having Diagnostic it follows you will attempt to develop Prognostics

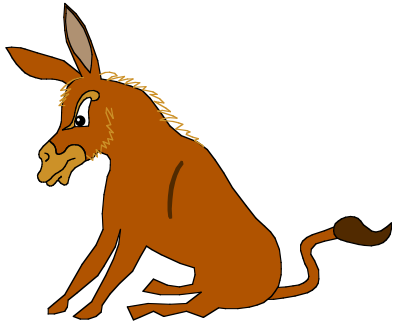
- Simple System Performance Degradation can be very Useful
  - Use on "low hanging fruit" where Trends can be easily Understood
  - Where Physics of Failure Models Not Available or Root Causes are Random
  - Without or before Accurate Useful Life Remaining Predictions

- Significant Data, Experience, and Maturation Time is Req'd to Develop Prognostics and Accurate Life Remaining Predictions
  - Plan for this with Resources, Maturation Strategy, Mgt Commitment

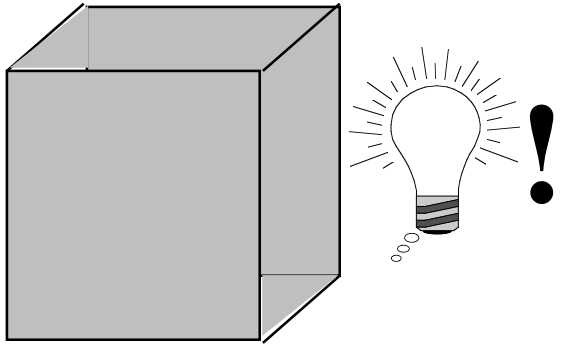
Lessons Learned

- **Prognostics with Accurate Useful Life Remaining Predictions**
  - Needs Multiple Types of Integrated Models
  - Physics of Failure Knowledge
  - Sensor based, Accumulated Usage, Fault Propagation, Statistical, etc.
- **Successful Develop of Global Prognostic Models Requires Multi-Discipline Team, Specialists, and Experts**
  - Material Science, State Awareness Sensor, Diagnostics Experts
  - Several Types of Modeling, Data Fusion, Probabilistic, Specific Component Design Specialists, etc.
  - Legacy Efforts often short on Material Science Expertise
- **Subsystem Expertise and Knowledge of Failure Critical**
  - It all Starts with the Subsystem Suppliers
  - Seeded Fault Tests Invaluable but Very Expensive – plan Wisely
  - Leverage off "Piggyback" Testing and Test Opportunities
- **Unlikely a Single Platform can Afford all the Resources Req'd**
  - Smart Strategy to Share Development Costs Across
  - Aggressively Use "Outside" S + T Efforts and Opportunities
- **Justify Benefits and Prepare for Funding Challenges**

The Question is:
Why Not PHM and CBM?



People resist change.



Protect rice bowls

Limited vision.

Problem is not in the capabilities, technologies and expected benefits; but in having the wrong people in the right positions, making the wrong decisions

Summary

- **PHM Is the Key Enable for the Auto Log Concept and the Implementation of CBM**
- **Technology is Now NOT the Limiting Factor**
  - **And It will Only Improve With Time**
- **All Elements Are Coming Together To Enable Our Visions of Advanced Diagnostics, Real Prognostics and Health Management, Auto Log, and CBM**
- **Must Implement and Apply Smartly and Wisely to Maximize Affordability Benefits**
- **PHM and CBM Must Be a Critical Element in all System Design Trades to Achieve Envisioned Reduction in Total Ownership Cost**

Successful PHM Implementation Is Achievable and Critical to JSF Program Goals